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TECTONIC EVOLUTION OF SULAWESI AREA: IMPLICATIONS FOR PROVEN AND PROSPECTIVE PETROLEUM PLAYS

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ABSTRACT

Sulawesi was formed by collision between drifted part of southeastern Sundaland and drifted microcontinents of the Indian-Australian Plate. The collision took place during Oligocene-early Pliocene, forming four arms of megatectonic provinces of Sulawesi and adjacent islands. The northern arm is composed of late Paleogene to Neogene subduction-related volcanic arc. The east and southeast arms are composed of Mesozoic and younger metamorphic and ophiolitic rocks resulted from Oligocene obduction. The south arm is dominated by Neogene volcanic rocks superimposed on the Mesozoic basement and Paleogene sediments of southeastern Sundaland. The fourth megatectonic province is the Late Paleozoic to Mesozoic Australian-derived microcontinents docking to eastern Sulawesi, comprising Buton-Tukang Besi and Banggai-Sula microcontinents. Surrounding Sulawesi, are deep marginal seas formed by rifting and opening, including the Makassar Strait, Tomini Bay (Gorontalo Basin), Gulf of Bone and Sulawesi/Celebes Sea.

Petroleum have been explored in Sulawesi since early 1900s. Discoveries and production have taken place in several areas. Complicated tectonic evolution provides diverse petroleum plays/ systems both at onshore and offshore areas of Sulawesi. A number of sedimentary basins were formed as response to tectonic evolution. Petroleum plays related to Paleogene rift basins, prolific in western Indonesia, combined with Neogene foreland basins are available and prospective in the Makassar Strait, onshore western Sulawesi, Gulf of Bone, and Gorontalo Basin. Asphalt and oil have been produced from collision-related foreland basins of Buton and Banggai, respectively. Large gas fields have been discovered in the Neogene reefal carbonates of the Banggai platform. Gas has been produced from the late Miocene reefs of the south arm of onshore Sulawesi and their prospectivity continues offshore into the Gulf of Bone. Mesozoic petroleum plays are prospective in deeper parts of the Gorontalo, Buton and Banggai Basins.

Application of recent knowledge on tectonic evolution of Sulawesi has improved exploration efforts in this area, maximizing their successes and minimizing their risks.

INTRODUCTION

Tectonically, Sulawesi is very complicated. Sulawesi formed along the Oligocene-Miocene collision zone between the Eurasian Plate and the micro-continental fragments derived from the Indo-Australian Plate. The K-shape of the island is peculiar and was resulted from a number of tectonic episodes.

Petroleum has been explored in Sulawesi since early 1900s by Dutch. Yet, it was not intensively explored. Prolific discoveries in Sumatra, Java and Kalimantan caused Dutch concentrated their exploration and production in these islands and most areas in Sulawesi remain unexplored, except asphalt production from Buton Island, SE Sulawesi.

Modern periods of exploration started in late 1960s when the Government of Indonesia opened investment in oil and gas using production sharing contract. A number of foreign oil companies explored western and South Sulawesi during 1970s and early 1980s resulting in discoveries of three gas fields (total resources 750 BCFG) in Sengkang area, South Sulawesi (gas was started to produce in early 2000s). Exploration in eastern Sulawesi during 1980s was awarded by discoveries of gas and oil (such as Matindok and Tiaka) but not yet developed at that time (Tiaka oil field was started to produce in 2006). Further exploration in eastern Sulawesi show good prospectivity of this area as proved by a number of gas discoveries during 2000s. Exploration in SE Sulawesi is not yet success, neither in western Sulawesi and offshore areas surrounding Sulawesi.

By the advent and wide usage of plate tectonics started in 1970s and terrane concept in mid-1980s, as well as many scientists worked out Sulawesi, geology and tectonics of the island is quite well understood although there are still problems yet unsolved and await comprehensive explanations. Applying recent knowledge on geological and tectonic evolution of Sulawesi to petroleum geology has been proven to be effective and could improve the opportunity of exploration success due to good understanding of geotectonics of basins to be explored and its implications to petroleum system.

The paper will discuss recent understanding of tectonic evolution of Sulawesi and surrounding islands and its implications to petroleum plays, both proven and prospective.

DATA & METHODS

The paper is based on study of both published literatures and unpublished data encompassing recently acquired seismic sections and recent results of exploration in and surrounding Sulawesi both onshore and offshore. Both existing and new interpretations are presented. To address the goal of the paper, literatures from various publications and unpublished data were collected, examined, analyzed and put in the interpretation and synthesis, composing this paper considering the framework and goal of the paper.

RESULTS AND DISCUSSION

Regional Setting

Sulawesi is located in an exceedingly complex tectonic region, where three major plates have been interacting since the Mesozoic (*Figure 1*). With reference to the hotspot frame the Pacific-Philippine plate is moving WNW, the Indo-Australian plate NNE and both are colliding with the relatively stable Eurasian plate (Sukamto, 1975; Hamilton, 1979; Daly et al., 1991). The convergence zone of this triple junction is a composite domain of micro-continental fragments, accretionary complexes, melange terrains, island arcs and ophiolites. Successive accretion from the east of oceanic and microcontinental material, and the associated development of island arcs, have all controlled the stratigraphic development of Sulawesi (Wilson and Bosence, 1996).

Sulawesi accommodated collision between fragment of Sundaland (western and South Sulawesi) and fragments of Australian plate (Buton-Tukang Besi and Banggai-Sula) (*Figure 1*). The history of this collision is also manifested on biogeographic nature of Sulawesi where in this island flora and fauna of Oriental realm (Sundaland) meet flora and fauna of Australasian realm. Alfred Russel Wallace, a British naturalist exploring Indonesia for eight years (1848-1852), including Sulawesi, defined the biogeographic borderline between these two realms in 1863, later called as the Wallace's Line, around Sulawesi. Further discussion on this, that Wallace's Line is geologically controlled can be found in Satyana (2011).

Knowledge that western and South Sulawesi was part of Sundaland is shown by the presence of Cretaceous active margin in South Sulawesi (*Figure 2*). This margin is interpreted to have run the length of Sumatra into western Java and then continued northeast through southeastern Borneo and into western Sulawesi, as suggested by the distribution of Cretaceous high pressure–low temperature subduction-related metamorphic rocks in central Java, the Meratus Mountains of southeastern Kalimantan and western Sulawesi. Western Sulawesi and eastern Java are underlain in part by Achaean continental crust, and geochemistry and zircon dating indicates derivation of this crust from the west Australian margin. Subduction ceased in the Late Cretaceous following collision of this block with Sundaland (Hall, 2009).

Neogene Sulawesi is inadequately understood and has a complex history still to be unraveled (Hall, 2009). In eastern Sulawesi, collision initially resulted in thrusting of ophiolitic and Australian continental rocks. However, contractional deformation was followed in the Middle Miocene by new extension. There was Miocene core complex metamorphism in north Sulawesi, extensional magmatism in south Sulawesi, and formation of the deep Gorontalo Bay and Bone Gulf basins between the arms of Sulawesi. Compressional deformation began in Pliocene, partly as result of the collision of the Banggai-Sula microcontinent in east Sulawesi, which caused contraction and uplift. Geological mapping, paleomagnetic investigations, and GPS observations indicate complex Neogene deformation in Sulawesi, including extension, block rotations, and strike-slip faulting. There are rapidly exhumed upper mantle and lower crustal rocks, and young granites, near to the prominent Palu-Koro strike-slip fault. During the Pliocene, coarse clastic sedimentation predominated across most of Sulawesi as mountains rose. The western Sulawesi fold-thrust belt has now propagated west into the Makassar Straits. At present, there is southward subduction of the Celebes Sea beneath the north arm of Sulawesi and subduction on the east side of the north arm of the Molucca Sea toward the west.

Tectonic Provinces of Sulawesi

Sulawesi is situated in a tectonically complex region between three major plates (Eurasia, Indo-Australia and Pacific/Philippine Sea). The present day setting is mirrored by the complexity of the pre-Tetiary and Tertiary geology of this island. Sulawesi is an assemblage resulted from tectonic collision of terranes/micro-continents coming from Sundaland and Australian areas. Formation of the island has occurred since Oligo-Miocene.

Sulawesi is formed of distinct north-south trending tectonic provinces (Sukamto, 1975) which are thought to have been sequentially accreted onto Sundaland during the Cretaceous and Tertiary. These form the four arms of Sulawesi and adjacent islands making four distinct megatectonic provinces (Bergman et al., 1996; Moss and Wilson, 1998) (*Figure 3*). The northern arm is composed of late Palaeogene to Neogene subduction related volcanic arc rocks resulting from the west-dipping subduction of the Molucca Sea Plate and south-dipping subduction of the Sulawesi Sea Plate. The east and southeast arms are composed of Mesozoic and younger allochthonous metamorphic and ophiolitic rocks which were obducted during the Oligocene time (Moss and Wilson, 1998). The south arm is dominated by Miocene and younger volcanic and plutonic rocks which form a magmatic belt superimposed on the Mesozoic basement of the southeastern margin of Sundaland. The fourth megatectonic province contains Late Palaeozoic and Mesozoic Australian-derived micro-continents which have been accreted to the eastern margin of Sulawesi, comprising Buton, Tukang Besi, Kabaena, Banggai and Sula, among other islands. Central Sulawesi and parts of the SE arm of Sulawesi are composed of sheared metamorphic rocks, including materials of both continental and oceanic derivation. These rocks are locally affected by high pressure metamorphism forming blueschists.

Neogene Orogeny of Sulawesi

Neogene period is the most important tectonic episode forming present configuration of Sulawesi. The episode is called Sulawesi Orogeny by Simandjuntak and Barber (1996). The orogeny was initiated by the collision of the two microcontinental blocks of Buton-Tukang Besi and Banggai-Sula with the eastern part of the island (*Figures 4, 5, 15, 16*). These two microcontinental blocks, having separated from the northern margin of Australian continent were carried westwards along the Sorong transcurrent fault zone by movements of the Philippine Sea Plate and collided with the eastern margin of the ophiolite complex. The collision caused the obduction of the ophiolite onto the microcontinental blocks and the shortening and thickening of the ophiolite by imbrication. The leading edges of the Buton-Tukang Besi and Banggai-Sula microcontinents were thrust beneath the ophiolite, uplifting the tightly folded, faulted and imbricated ophiolite and its pelagic cover to heights of more than 3000 m above sea level.

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. Satyana et al. (2007) and Satyana and Purwaningsih (2011) argued that the uplift in collisional tectonics related to gravity exhumation of once subducted leading edges of microcontinents resumed again. Before the collision, the leading edges of both Buton and Banggai subducted beneath Eastern Sulawesi. Subduction ceased with the advent of collision. The junction between subducted oceanic crust and the leading edges of the microcontinents broke off due to the buoyancy of the continental crust relative to the astenosphere, and these continental parts began to exhume by gravity tectonics, causing collisional uplifts. Satyana and Purwaningsih (2011) 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.

Also as a result of the collision the metamorphic belt of Central Sulawesi was thrust westwards over West Sulawesi and uplifted to form mountain ranges of nearly 3000 m. Overthrusting resulted in the formation of a foreland fold and thrust belt in Tertiary sediments, the Majene Fold Belt, which continues to develop westwards to the present day, affecting Recent sediments in the Makassar Strait.

The K-shaped Sulawesi Island is considered as a response to post-collision rotation of the curvatures of four arms of Sulawesi from originally being convex eastward to being concave eastward (Satyana, 2006). The curvatures of four arms of Sulawesi represent normal couple of magmatic arc (southern and northern arms) and subduction/ophiolitic arc (eastern and southeastern arms). These arcs was considered originally convex to the open sea (eastwards) as a result of west-dipping subduction zone. All arcs formed in plates convergence zone globally always convex to the ocean as response to the geometric rule of Euler principle. However, present curvatures of Sulawesi are concave to the ocean (eastwards). This is considered as the response of the magmatic and subduction arcs when they were collided by Buton-Tukang Besi and Banggai-Sula microcontinents frontal to these curvatures from the east. This collision has rotated all arms of Sulawesi from being convex to concave relative to the open ocean and presently resulting in K-shaped of Sulawesi curvatures. These rotations have been partly proved by paleomagnetism. Opening of the Gulf of Bone is due to rotation of Southeast Arm of Sulawesi anticlockwisely.

Associated with the collision, or following shortly after, was the development of the NNW-SSE trending Palu-Koro sinistral transcurrent fault, along which eastern Sulawesi has been displaced northwards with respect to western Sulawesi. More recent transtensional movements during the Quaternary, continuing to the present time, are responsible for opening pull-apart basins, such as those of lakes of Poso, Matano and Towuti, as well as Palu depression. Recent earthquakes along the Palu-Koro and related faults show that the system is currently active.

Tectonic Evolution of Sulawesi

The making of Sulawesi involved geologic and tectonic processes including: the separation of western Sulawesi from the Sundaland by the opening of the Makassar Straits, the attachment of eastern Sulawesi and Buton-Tukang Besi as well as Banggai-Sula Islands by subduction, accretion, and collision (Moss and Wilson, 1998). *Figures 4 and 5* show tectonic and palaeogeographic reconstruction of Sulawesi during Paleogene and Neogene.

Large areas of western Sulawesi (and eastern Kalimantan) had been accreted onto southwestern Borneo, part of the eastern margin of Sundaland, by the Cenozoic (Late Cretaceous). Subduction of the Indian Ocean, Philippine Sea and Molucca Sea plates has been responsible for the progressive collision and accretion of fragments of continental and oceanic crust along the eastern margin of Sundaland. Western Sulawesi and Gulf of Bone is considered as the eastern margin of the Sundaland.

Eocene

West, central and parts of the SE arms of Sulawesi are regarded as a region of microcontinental material forming a contiguous land area during the early Paleogene. Much of mainland SE Asia, southern Borneo and western Sulawesi appears to have been emergent during the Paleocene and the early Eocene. Volcanic arcs are inferred to have existed along the north arm of Sulawesi and the eastern side of west Sulawesi, perhaps extending down through Java from the Eocene until the late Oligocene. Geochemistry and dating of calc-alkaline rocks and interbedded sediments in eastern South Sulawesi suggests there was a volcanic arc in this area during the Paleogene (Sukamto, 1975; Leeuwen, 1981). Paleogene basic volcanics and volcaniclastic lithologies are also present in western central and northern Sulawesi. There was widespread basin formation in middle Eocene times around the margins of Sundaland. Much of eastern Borneo, western Sulawesi, the Makassar Straits and the east Java Sea was an area of Tertiary sedimentation, in which the depositional environments varied between fluvial, deltaic, shallow marine clastic and carbonate shelves and areas of deeper water sedimentation.

Evidence for Eocene extension, block faulting and subsidence is seen on seismic lines crossing the Makassar Straits, and this was the time when the land connection between Borneo and Sulawesi was severed. The Makassar Strait is thought to be underlain by attenuated continental crust (Durbaum and Hinz, 1982) and stretching occurred between early Palaeogene and early Miocene (Situmorang, 1982). Hall (1996) considered the period of extension of the Makassar Strait is assumed to be 44-34 Ma which is consistent with the stratigraphic interpretation of Situmorang (1982, 1987).

Sea floor spreading began in the marginal oceanic basin of the Sulawesi Sea in the mid-Eocene (Rangin and Silver, 1990) and may have influenced basin initiation in Borneo and Sulawesi (Hall, 1996). In western south Sulawesi marginal marine clastics and coals are conformably overlain by a thick shallow marine carbonate succession. By late Eocene times, shallow marine carbonate sedimentation had been established over much of south Sulawesi and southwestern central Sulawesi although these areas were separated by a deep marine basinal areas (Wilson and Bosence, 1996).

Oligocene

Flat-lying reflectors seen on seismic sections across much of the north and south Makassar basins suggest deep marine sedimentation occurred in a uniformly subsiding basin during the Oligocene (Situmorang, 1982). Oligocene deep marine sedimentation also occurred in some areas of western central Sulawesi. Extensive shallow water carbonate platform developed or continued to accumulate sediment during the Oligocene, while deeper water marls were deposited in adjacent areas. Ophiolites of east and SE arms of Sulawesi detached in an oceanic setting at this time and emplaced later based on metamorphic ages of 28-32 Ma obtained from at the base of the East Sulawesi ophiolite (Moss and Wilson, 1998). Palaeomagnetic work shows that lavas of the east Sulawesi ophiolite have a clear southern hemisphere origin (Mubroto et al., 1994) and formed at a latitude of 17 +/- 4°S. The age and origin of the east Sulawesi ophiolite is uncertain. Ages proposed by previous authors range from 93-16 Ma, mostly older than 30 Ma. Since the ophiolite and west arm were juxtaposed by the early Miocene (Moss and Wilson, 1998), the ophiolite is fixed to west Sulawesi from 25-0 Ma and before 25 Ma moved with the Indian plate.

The microcontinental blocks of Buton-Tukang Besi and Banggai-Sula, although drifting westwards towards Sulawesi, had yet to be accreted onto Sulawesi. These blocks rifted from the Australian-New Guinea continent during the late Mesozoic (Audley-Charles, 1974; Pigram and Panggabean, 1984).

Miocene

Shallow marine carbonate deposition continued on high blocks in southern and western central Sulawesi until the middle Miocene, surrounded by deep marine sedimentation. The East Sulawesi ophiolite had been accreted onto western Sulawesi, and it is inferred that land areas were emergent in central Sulawesi during at least part of the Miocene as a result of this collision. In the north arm of Sulawesi island arc basalts were erupted during the Oligocene and Miocene. They are interbedded with shallow marine carbonate deposits, and volcanic islands are inferred to have been emergent. Between the middle Miocene through to the earliest Pliocene a volcanic arc developed along the length of western Sulawesi (Yuwono et al., 1987; Bergman et al., 1996). During the Neogene a volcanic arc also occurred along the north arm of Sulawesi and possible island chain connections may have existed to the Philippines.

The microcontinental blocks of Buton-Tukang Besi and Banggai-Sula were accreted onto eastern Sulawesi during the Miocene or earliest Pliocene. On Buton, obduction of ophiolitic material and the reworking of pre-Miocene strata into clastic deposits has been related to early to middle Miocene collision with SE Sulawesi (Davidson, 1991). Prior to collision, deep marine sediments were deposited on Buton, although uplift and thrusting associated with collision would have created emergent land areas in the middle Miocene. Collision of Banggai-Sula microcontinent occurred in the latest Miocene to early Pliocene (Garrard et al., 1988).

Pliocene-Recent

By the Pliocene, the coastline of Sulawesi was similar to the present. Major shallow water carbonate areas persisted on the east and west sides of the Makassar Straits. The final juxtaposition of the fragments that comprise Sulawesi occurred between the Pliocene and the present. Although most authors infer that internal rotation and juxtaposition was achieved via a system of linked strike-slip faults and thrusts, the linkage and displacements along faults is still contentious. Collisions and subduction east of Sulawesi caused transpression during the Neogene and Quaternary which resulted in uplift of extensive areas in Sulawesi and caused rapid uplift of a number of high mountain areas, particularly in central Sulawesi (Bergman et al., 1996). The transpressive regime also resulted in extension and subsidence in other areas. Bone Bay separates the south and SE arms of Sulawesi is suggested to have developed as an extensional feature in the late Oligocene (Davies, 1992). Seismic data suggests that the shape of Bone Bay was then further modified during the Miocene/Pliocene by transpressive and transtensional movements. Igneous activity continued in western Sulawesi until the Pliocene and Pleistocene and is similar in nature to the late Miocene volcanics in the same area (Bergman et al., 1996). Along the north arm of Sulawesi, Miocene to Pliocene volcanism is related to south-dipping subduction of the Sulawesi Sea oceanic crust under the north arm of Sulawesi. A string of active Quaternary to Recent volcanoes dominate the Sangihe Islands and the eastern part of the Minahasa region, and are related to west-dipping subduction under this area.

Tectonic reconstruction is usually constrained by palaeomagnetics. However, there has been little palaeomagnetic work on Sulawesi. The earliest results by Haile (1978) from the SW and SE arms indicated that these arms originated in different regions during the Late Jurassic-Early Cretaceous. This supports the consideration that Sulawesi is assembled by various terrane coming from various sources. Data from SW Sulawesi indicate that it was close to its present latitude in the Late Jurassic (Haile, 1978) and late Palaeogene (Sasajima et al., 1980) but rotated clockwise by around 45° between the late Palaeogene and late Miocene (Mubroto, 1988 *in* Hall, 1996). Sasajima et al. (1980) reported Eocene-early Miocene clockwise rotation of the east part of the north arm or clockwise rotation of more than 90° by the north arm between the Eocene-early Miocene. Surmont et al. (1994) show that 20-25° clockwise rotation of the whole north arm has occurred since the Miocene but that larger rotations are related to local shear zones. This supports the consideration that post-collision tectonics in Sulawesi is manifested by rotation of Sulawesi's arms (Satyana, 2006).

Deep Sea Basins Surrounding Sulawesi

Four marginal deep sea basins occur surrounding Sulawesi, namely the Makassar Straits (Makassar Strait Basin), Gulf of Bone (Bone Basin), Tomini Bay (Gorontalo Basin) and Sulawesi/Celebes Sea. Most of these basins were formed by rifting in the eastern margin of the Sundaland (Satyana, 2010) started in the Eocene following Late Cretaceous accretion.

The Makassar Straits

East Borneo and West Sulawesi were part of a single area in the Late Mesozoic but were separated during the Cenozoic by the opening of the Makassar Straits. The Makassar Straits formed by rifting (*Figure 6*). There has been debate about the age of formation of the straits between Neogene and Paleogene. Eocene age for the opening is now generally accepted. Extension began in the Middle Eocene and formed graben and half-graben above which is an important unconformity of probable Late Eocene age. The unconformity marks the top of the synrift sequence. Thermal subsidence continued during the Oligocene. Flexural subsidence due to loading on the west and east sides may have deepened the straits, as inversion in eastern Kalimantan migrated east and the Mahakam delta prograded east since the Early Miocene, while folding and thrusting of western Sulawesi migrated west since the Early Pliocene.

The mechanism of the opening has also been the subject of controversy. Most authors have favored an extensional origin for the straits. The nature of crust underlying the straits has also long been the subject of scientific debate between continental and oceanic. Most authors agree with attenuated (due to rifting) continental crust composing the South Makassar Strait, but the basement for the North Makassar Strait which is much deeper than that of the South Makassar Strait is difficult to determine. There have been much arguments arguing that the North Makassar Strait is floored by oceanic crust however, another possibility that the strait is floored by attenuated continental crust is also possible. Flexural loading model, gravity-magnetic model and seismic data show variable interpretations hence complicating the matter. Altered volcanic rocks penetrated at the base of the recent well of Rangkong-1 (ExxonMobil, 2010) in north Makassar Strait reveal continental arc - signatures hence supporting a consideration of attenuated continental crust as the basement of the Makassar Strait.

However, the nature of the basement to the central part of the Makassar Straits can be interpreted only indirectly, because the very thick sediment cover and the great depth to basement means that no direct sampling is possible. The oceanic crust interpretation is favored by the great width of the extended zone and, in particular, the 200 km width of the deepest part of the straits where depths are close to 2.5 km water depth and there are several kilometers of almost undisturbed flat-lying sediments above the basement. The continental crust interpretation is favored by the observations that rifting structures can be seen below the basal unconformity. Gravity and magnetic modeling show attenuated continental crust floors northern Makassar Straits. Half-graben and graben are evident in places, and the pattern of faulting mapped below the basal unconformity is similar to that expected from oblique extension of a basement with a pre-existing NW–SE fabric. Structures can be seen above the unconformity which could be carbonate build-ups on tilted fault blocks or volcanic edifices.

The NW–SE lineaments which segment the basin are interpreted to be Cretaceous or Paleocene structures, which in places may have been reactivated. The northern margin of the Paternoster Platform is clearly a major steep fault with about 2 km of normal offset of the Eocene and the large displacement is inconsistent with an oceanic transform fault.

Free-air gravity shows there is a broad gravity low beneath the central North Makassar Basin. This includes an elongated low northeast of the Paternoster Platform that follows the narrow trough connecting the North and South Makassar Basins, and an irregular low between the Mahakam delta and the Mangkalihat Peninsula. There is large gravity high beneath the Mahakam delta depocenter. In the last few years more than 10,000 km of new data have been acquired or reprocessed by TGS-NOPEC Geophysical Company during seismic surveys covering large parts of the North Makassar Straits. The bathymetry in the North Makassar Straits reflects some obvious features of the deeper structure. The seafloor in the central North Makassar Straits is flat and undeformed. In the north the water depth is almost 2500 m and is about 200 m less in the south. Depths decrease towards the carbonate-dominated Paternoster Platform in the south and the Mangkalihat Peninsula in the north. To the west, the seafloor rises gradually to the very shallow East Kalimantan Shelf, crossing the front of the Mahakam delta. In the east, the seafloor shallows towards western Sulawesi, rather more abruptly than on the west side, reflecting folding and thrusting of a deformed zone that is now described as the Offshore West Sulawesi Foldbelt.

From south to north, the Offshore West Sulawesi Foldbelt can be divided into three provinces (Puspita et al., 2005): the Southern Structural Province (SSP), Central Structural Province (CSP) and Northern Structural Province (NSP) based on seafloor characteristics, subsurface deformation, in particular the character and position of the deformation front. The Cenozoic sedimentary sequence in the central part of the North Makassar Straits is undeformed and separated from the Offshore West Sulawesi Foldbelt by a change in slope at which there are folds, and blind and emergent thrusts and backthrusts.

The Gulf of Bone

The Gulf of Bone separates the eastern and western arcs of Sulawesi. It is thought to be the result of extension (*Figure 7*).

Sudarmono (1999) interpreted that the Bone Basin is a composite basin, with its origin as a subduction complex and suture between Sundaland and Gondwana-derived micro-continents. It subsequently evolved as a submerged intra-montane basin. The basin had two major periods of development: (a) Paleogene to Early Miocene, and (b) Early Miocene to Recent. Originally, the basin probably occupied a forearc setting as part of a westward subduction complex during the Paleogene to Early Miocene. Subsequently, westerly plate convergence of Australian-derived micro-continents toward the subduction complex during the Middle to Late Miocene, dramatically changed the style of deposition, structural framework, and configuration of the basin. A Middle Miocene collision of the microcontinents with the subduction-related accretionary complex, followed by collision of the microcontinents with West Sulawesi, built orogens surrounding the Bone Basin which shed large volumes of sediment into the northern depocenter of the Bone Basin.

The collision led to an eastward rotation of Southeast Sulawesi, which resulted in rifting and submergence of the southern part of the basin. The two colliding plates began to lock during the Pliocene, and the continued plate convergence was accommodated by strike-slip movements along the Walanae, Palukoro and many other faults. Subsequently the Bone Basin submerged into an intra-montane basin setting. Clastic sediments derived from surrounding mountains to the east, north and west were deposited progradationally southward toward the depocenter of the basin. Strike-slip movements are still active, and the bathymetry of the Gulf of Bone reflects the present day tectonic activity.

Recent data (2007) acquired by TGS Nopec in the Gulf of Bone (4,687 km of 2D seismic data with grid spacing 10 km to 30 km, 11,564 km of gravity and seismic) give another interpretation of the Bone Basin. The Bone Basin is rifted basin like rifted basins of Western Indonesia surrounding the Sundaland. Accordingly, the Bone Basin represents the basin that developed in the eastern margin of the Sundaland. There is no appearance of typical forearc basins as previously interpreted. Eocene deep, thick synrift package developed. Late Miocene potential reefal buildups grew on both basin flanks. A platform to the southeast and volcanic high to the west restrict the synrift to early post rift sediment accumulation. Numerous basement highs appear to be capped by Late Miocene carbonates/reefs. Deep synrift sections developed in north, central and south of the basin.

Bone Basin may an Eocene rift basin, formed together with Makassar Straits and other Eocene rift basins in response to far-field extensional stresses. Whether the basin is an Eocene forearc or rift basin, the key difference is in the interpreted edge of Sundaland at the onset of Eocene extension. Compilation and analysis of all onshore and offshore geologic and geophysical data may resolve the issue.

The nature of the basement of Bone Basin is not known. Yulihanto (2004) interpreted that the basin is floored by oceanic crust in the centre and continental crust on the flanks. Basin depocenter is restricted by the West Bone Bay Fault Zone and the East Bone Bay Fault Zone.

The Tomini Bay (Gorontalo Basin)

Prior to 2005 no seismic data coverage or offshore wells existed for the Gorontalo Basin. In 2006, following encouraging interpretation of the 2005 'new look' deep recording 2D reconnaissance non-exclusive seismic survey, some 5800 line kilometers of 2D non-exclusive seismic data was acquired. Subsequent interpretation of this data (Jablonski et al., 2007) revealed a new geological picture that challenges pre-existing ideas about tectonic development and the hydrocarbon prospectivity of the region.

The Gorontalo Basin has a stack of rifts from Mesozoic and Tertiary (*Figure 8*). Eocene rift grabens similar in geometry to the fluvio-lacustrine source rock-rich megasequences that underlie many oil-prone petroleum systems surrounding the Sundaland. The current geological positioning of the Gorontalo Basin is the result of older, Mesozoic collisions of Australian micro-plates with Sundaland. This has been followed by the Eocene stretch of Sundaland. A relatively quiescent period of widespread carbonate platform deposition, with some intrusions associated with volcanic arc processes, ensued during the Oligocene to Middle Miocene. This depositional system was disrupted in the latest Miocene, with increased clastic deposition mostly terminating carbonate platform in eastern Indonesia. Carbonate pinnacle growth with localized deposition of clastic deltas was established—a system that continues today.

Contrary to widespread belief, the Gorontalo Basin appears to have a similar geological history to the neighboring Makassar Basin. Extensive continental crust has been identified to underlie the Gorontalo Basin. This is in contrast to the general view that a relatively young sedimentary basin is underlain by oceanic crust. The present-day central Sulawesi 'Neck' appears to be a relatively recent feature caused by the Pliocene to Recent compression. A pre-Eocene collision has also been identified, elucidating the break-up history of Gondwana and present-day eastern Indonesia. Despite the complexity of the onshore geology, which displays mostly compressional features, the offshore region of the Gorontalo Basin predominantly displays extensional tectonics. Large structures at multiple stratigraphic levels are similar to the Makassar and Banggai basins. , where there have been a number of significant hydrocarbon discoveries. While still classified as a frontier region, the Gorontalo Basin offers an offshore opportunity that challenges the perception of the region.

The Sulawesi/Celebes Sea

The central West Philippine Sea, the Sulawesi Sea and the Makassar Straits may form parts of a single marginal basin which opened between late Eocene and mid Oligocene and widened eastwards like the present South China Sea (Hall, 1996).

Celebes Sea Basin is considered as an extinct marginal sea lying between Sulawesi and the Sulu Sea (Hutchison, 1989). On his reconstruction, Hall (1996) considered the Celebes Sea as the basin consistent with a backarc setting related to northward subduction of the Indian ocean lithosphere beneath west and north Sulawesi from middle Eocene to early Miocene.

The sea floor is fairly smooth and mostly lies at depths of between 4 and 5 km. Seismic profiles indicate an oceanic crust, overlain by sediment thicknesses varying from 2 to 3 km (Djajadihardja et al., 2003; *Figure 9*). The crustal age is considered as 51 Ma based on modeling of heat flow measurements. The magnetic anomalies are identified as anomalies 30-33, trending 65°E representing crustal ages of 65-72 Ma, indicating a Late Cretaceous episode of sea-floor spreading (Lee and McCabe, 1986). However, the anomaly identification cannot be considered to be of high reliability, for Weissel (1980) had previously identified them as anomalies 18-20, representing ages of 46-52 Ma (middle Eocene) which parallel the Sulu ridge and young to the south, into the North Sulawesi Trench.

Silver and Rangin (1991) concluded that the Celebes Sea was either a marginal basin formed behind an arc or is a trapped fragment of a larger entity, including the Molucca Sea now separated from it by the narrow Sangihe Arc. Assuming the arc is not allochthonous the Celebes Sea has a backarc relationship (Packham, 1996) to Paleogene volcanic rocks in the north arm of Sulawesi and the eastern part of the southwest arm where they have been broadly dated as lower Eocene to upper Oligocene.

Implications for Petroleum Plays

Tectonics configure framework of sedimentary basins where petroleum may exist. Stratigraphic and structural setting of the basins are also controlled by tectonics. Subsidence and uplift of basins related to source maturation and concentration of accumulation respectively are also controlled by tectonics. Tectonics therefore, play significant roles on petroleum plays. Proven and prospective petroleum plays of Sulawesi are controlled by tectonics.

Sulawesi presents quite prolific hydrocarbon seeps onshore and offshore. Several fields have been discovered and produced (*Figure 10*).

Petroleum plays of Sulawesi can broadly divided into two kinds: (1) plays related to rifted basins of Sundaland type and (2) plays related to collisional basins of Australian microcontinents. Plays of Sundaland rifted basins are represented by rifted basins in Makassar Strait (*Figure 11*), west and south Sulawesi (*Figure 12*), Gulf of Bone and Gorontalo Basin (*Figure 13*). Plays of collisional Australian microcontinents are represented by collisional foreland basins of Buton and Banggai (*Figures 14-18*).

Plays of Sundaland Rifted Basins

Widespread synrift sequence across the whole or most of the Makassar Straits are potentially a greater number of exciting exploration targets in deeper water (Hall et al., 2009), see *Figure 11*. If the straits are floored mainly by oceanic crust, success will depend on organic material carried into deep water and distributed through sand-rich sequences which appears a riskier system. If the floors are thinned continental crust, there is possibility of the development of lacustrine source rocks in the rifts, with synrift reservoirs and carbonate build up growing on horst areas. However, facies changes from coally sources and lacustrine in onshore west Sulawesi into more marine source facies within synrift sources in the Makassar Strait should be considered. If the extension of rifting was too rapid, rapid sedimentation of synrift sediments would cause organic matters dilution causing low TOC. Wells drilled by ExxonMobil (Rangkong-1, 2010) or by Marathon (Bravo-1, 2010 and Romeo C-1, 2011) show no effective kitchen adjacent to this structure. Depression areas look like kitchens may just deep areas without minimum requirement for source capacity. Wells drilled in this area to date found good quality of Eocene-late Oligocene carbonates (Bacheller III et al., 2011) (*Figure 11*). Traps are also definitive. Traps may also associate with altered volcanics as penetrated by Rangkong-1 well. If volcanics are fractured or weathered resulting porous reservoirs, this is good. The most important aspect and risk here is charging of hydrocarbons.

Oil seeps in West Sulawesi onshore have been characterized geochemically and reveal the

Eocene sources of lacustrine to transitional/coal facies. Eocene sourced-oils are also indicated from Ranggas oil field reservoired by Miocene Kutei turbidite fans. The Eocene sources may come from the Eocene rifts of the Makassar Straits. This show that sources deposited in the Eocene rifts of Makassar Straits and West Sulawesi have generated oils. Miocene fold-thrust belts of western Sulawesi that continue into the offshore areas are prospective play. Critical review should be made for this play since the Miocene sediments were mostly sourced by volcanic provenances of western Sulawesi. Possibility of low-quality reservoirs due to volcanic-diagenetic clay and sediment immaturity related to near transportation should be anticipated. The presence of sources in Miocene volcaniclastic sediments should also be reviewed considering that volcanic sediments are organic lean. Miocene fold and thrust belts developed in thin-skinned tectonics where their detachment surface may play a role as barrier for migration from deep and older sources. Therefore, hydrocarbon charging is another issue for Miocene petroleum system.

Prospectivity of onshore south Sulawesi was discussed by Wilson et al. (1997) (*Figure 12*). Onshore south and west Sulawesi were the first areas in Sulawesi explored for petroleum. Proven source rocks, reservoir rocks, hydrocarbon generating kitchen areas and, most importantly, hydrocarbon accumulations exist in these areas (Wilson et al., 1997). The petroleum systems of South Sulawesi contain the following elements.

Sources - Coals and carbonaceous shales of the Eocene Malawa/Toraja Formation provide potential source lithologies. The rocks contain terrestrially influenced kerogens, and have TOC values in the range 31-81% and HI values ranging from 158 to 578 (Coffield et al., 1993). Mature oils from seeps have been typed to these Eocene source rocks in the Kalosi area.

Reservoir - Potential reservoir lithologies occur in the Eocene clastics and in overlying Tertiary carbonates. The best potential siliciclastic reservoirs are marine shoreface sandstones, with a low lithic content, 20-25% porosities, and moderate permeabilities, which occur towards the top of the Malawa/Toraja Formations. Platform carbonates of the Tonasa/Makale Formations are usually characterised by little primary or secondary porosity and low permeabilities. Redeposited facies, abutting faulted footwall highs, contain low to moderate porosities and permeabilities and are thought to comprise the most suitable lithogies for hydrocarbon reservoirs within these formations, and indeed traces of hydrocarbons do occur (Wilson, 1996). Proven thermogenic gas reservoirs are present in subsurface Miocene knoll reefs of the Tacipi Formation in the Sengkang Basin.

Conduits/Migration - Eocene deltaic sands associated with the coaly horizons are one of the primary inferred conduits for the migration of hydrocarbons. To fill potential clastic reservoirs in the Eocene section, neither fault nor cross-stratal migration is required for the system to work. Faults are another possible migration pathway for hydrocarbons. Outcrop examples of both oil and gas seeps along fault planes are present in the Kalosi area.

Seal - Tight clays and silts of the Walanae Formation, often rich in volcaniclastic components, comprise seal lithologies and are proven effective in the Sengkang Basin. Platform carbonates of the Tonasa/Makale Formations are a potential seal for reservoirs in the underlying Eocene clastic succession.

Trap - Isolated coral-rich carbonate knoll reefs comprise proven stratigraphic traps for gas accumulation in the Sengkang Basin (Grainge and Davies, 1983). Compressional anticlinal traps, with four-way dip closures, are inferred in the Kalosi area where there are examples of breached anticlines with oil seeps along their crestal axes (Coffield et al., 1993).

Timing - Known pre-late Miocene stratigraphic thicknesses are inadequate to depress the identified source rocks into the oil window in many parts of South Sulawesi. However, in areas where Tertiary deep marine basins formed and thicker sedimentary successions accumulated, such as the Walanae or Tempe Depression, source rocks are inferred to have been depressed into the oil window. Hydrocarbons were only generated in other regions possibly following Miocene magmatism and certainly during Pliocene orogenesis and thrust loading (Coffield et al., 1993).

While still classified as a frontier region, the Gorontalo Basin offers an offshore opportunity that challenges the perception of the region (Jablonski et al., 2007). An active petroleum system is suggested by east-west oriented depocenters with thicknesses locally exceeding 10 kilometers (*Figure 13*), the mostly southward focused hydrocarbon migration routes, and the presence of numerous onshore oil seeps along the southern edge of the Gorontalo Basin. Numerous Amplitude with Offset (AVO) anomalies observed on newly acquired seismic sections also suggest the presence of hydrocarbons at a variety of stratigraphic levels. The new seismic data indicate the following pre- Paleogene to Recent plays, some of which may contain stacked reservoir–seal pairs sourced by several Tertiary source rocks: older rift fault blocks associated with the Australian plate rifting, and subsequent collision with Borneo in the Cretaceous; Eocene rift fault-blocks; Oligocene to Middle Miocene platform carbonates; Late Miocene to Pliocene carbonate build-ups; Late Miocene to Recent lowstand deltas and turbidites.

In the Bone Basin, the Eocene rift interpretation implies a more favorable environment for hydrocarbon generation, and if proven could significantly reduce exploration risk in this frontier basin. ALF (airborne laser fluorescence) fluors have been detected in the northern and southern Bone Basin suggesting a working petroleum system. Synrift Eocene to Oligocene potential source package is up to >2.5 sec thick, areally extensive synrift package and buried by 2 –3.5 seconds of postrift sediments. ALF may be related to postulated hydrocarbon kitchen in very deep and mature half grabens. Traps are provided by combination of carbonate reefs, canyon fill and deep water turbidite plays. Numerous basement highs appear to be capped by Late Miocene carbonates / reefs. Play types of the Bone Basin may include: faulted anticlines, tilted fault blocks, carbonate reefs, stratigraphic subcrop plays, drape over basement highs, turbidite fans, slope channel fill, and stratigraphic pinchout. Gas fields of Kampung Baru complex (Walanga, Sampi-Sampi, Bonge) located in east Sengkang Basin, are proven play of Late Miocene Tacipi carbonate reefs.

Plays of Collisional Australian Microcontinent

Plays related to collision of Australian microcontinents (Buton-Tukang Besi and Banggai-Sula) to eastern Sulawesi are proven and still have remaining prospective structures (*Figures 14-16*). Mined asphalt fields (biodegraded oils) of Buton and oil production from Tiaka field and several significant gas discoveries in Banggai, show the proven plays related to collisional Australian microcontinents.

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.

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 (*Figures 14-16*). 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. Upper Cretaceous, Early to Middle Miocene, and Pliocene clastics and carbonates are potential reservoirs (*Figure 17*).

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.

The relationship between collision and petroleum in East Sulawesi - Banggai-Sula has been discussed by Satyana (2006) and Satyana and Purwaningsih (2011). Banggai-Sula micro-continent has two distinct structural styles, two contrasting sedimentary sequences, and two reservoir units (*Figure 17*). 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. 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 18*): (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 microcontinent. 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 postcollision extension, (2) sedimentation of postcollision/molassic deposits, playing a role as burial sediments, (3) subsidence of the basins due to deposition of molasses and/or thrust sheet of postcollision 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 postcollision wrench, and (6) charging/migration from subsided kitchen to updip area of the microcontinent where carbonate reefs developed or to thrusted anticlines formed by collisional deformation (Satyana et al., 2008; Satyana and Purwaningsih, 2011).

CONCLUSIONS

1. Sulawesi was formed by collision between drifted part of southeastern Sundaland and drifted microcontinents of the Australian Plate. The collision took place during Oligocene - early Pliocene, forming four arms of megatectonic provinces of Sulawesi and adjacent islands.
2. Tectonic evolution of Sulawesi involved tectonic processes from middle Eocene -early Pliocene including: separation of western Sulawesi from the eastern Borneo by the opening of the Makassar Straits, the attachment of eastern Sulawesi areas and Buton-Tukang Besi and Banggai-Sula Islands by subduction, accretion, and collision. Neogene period is the most important tectonic episode forming present configuration of Sulawesi. The episode is called Sulawesi Orogeny. The orogeny was initiated by the collision of Buton-Tukang Besi and Banggai-Sula microcontinents with eastern Sulawesi.
3. Four marginal deep sea basins occur surrounding Sulawesi, namely the Makassar Straits (Makassar Strait Basin), Gulf of Bone (Bone Basin), Tomini Bay (Gorontalo Basin) and Sulawesi/Celebes Sea. Most of these basins were formed by rifting in the eastern margin of the Sundaland started in the Eocene following Late Cretaceous accretion.
4. Tectonics configure framework of sedimentary basins where petroleum may exist. Stratigraphic and structural setting of the basins are also controlled by tectonics. Petroleum plays of Sulawesi can be broadly divided into two types: (1) plays related to rifted basins of Sundaland and (2) plays related to collisional basins of Australian microcontinents. Plays of Sundaland rifted basins are represented by rifted basins in Makassar Strait, west and south Sulawesi, Gulf of Bone and Gorontalo Basin. Plays of Australian collisional microcontinents are represented by collisional foreland basins of Buton and Banggai and possibly Gorontalo Basin.

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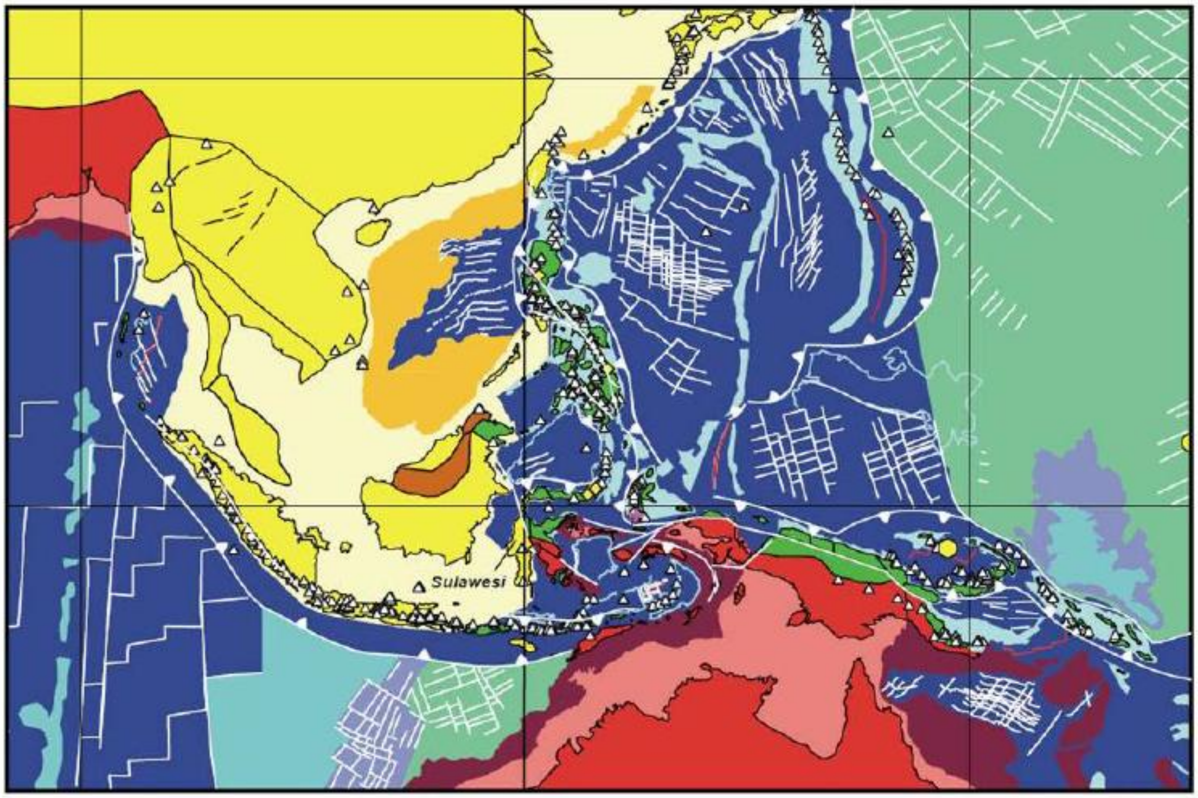
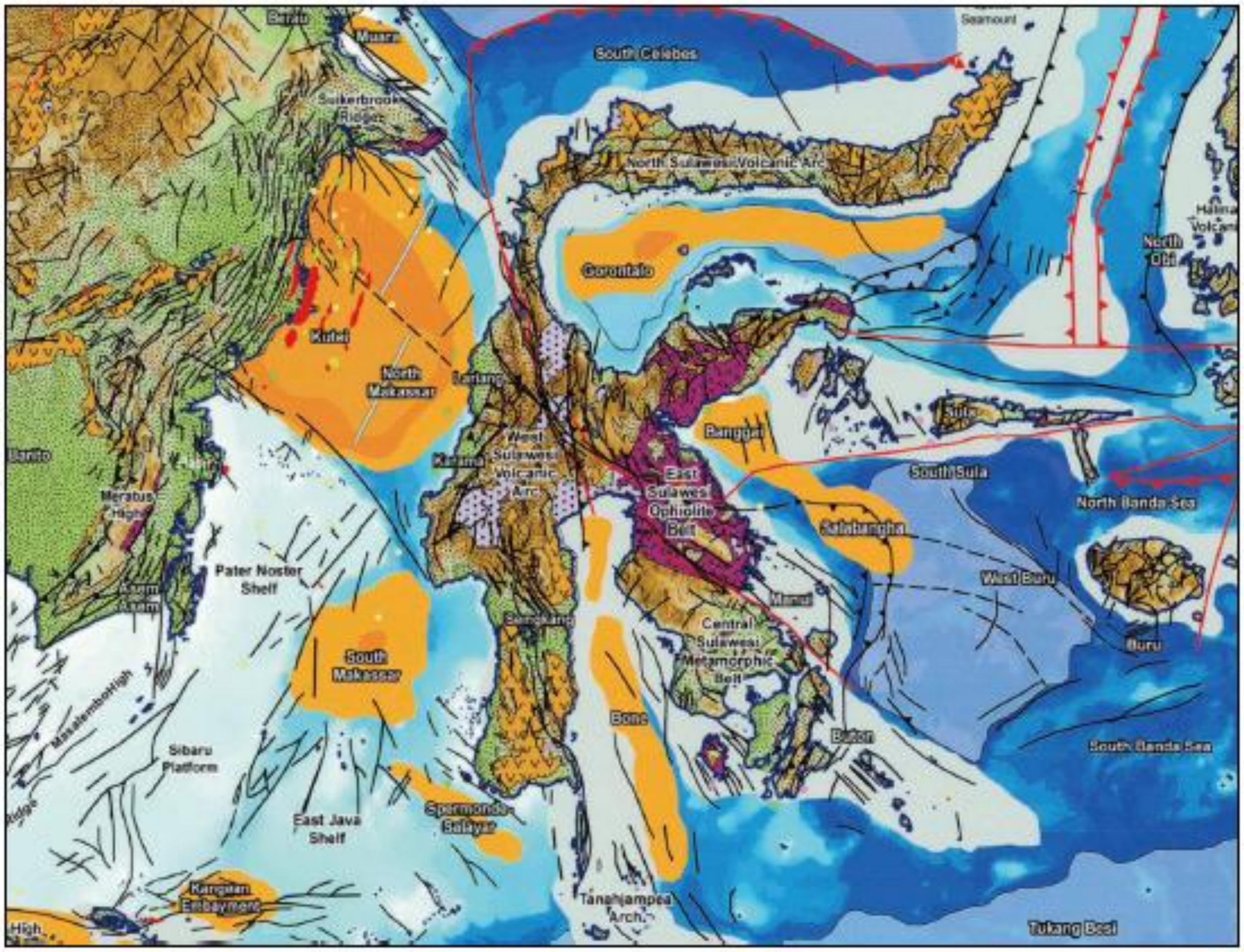


FIGURE 1: Map of SE Asia and Austral-Asia showing present tectonic configuration (Hall, 1996). Colour represents crustal assemblages. Yellow represents Asiatic assemblage, red represents Indian-Australian assembalge, green in islands represent oceanic assemblage. White strips in ocean are magnetic anomalies recording sea-floor spreading. Note Sulawesi is an assemblage of many crustal terranes: Asiatic, Australian, and oceanic in between.



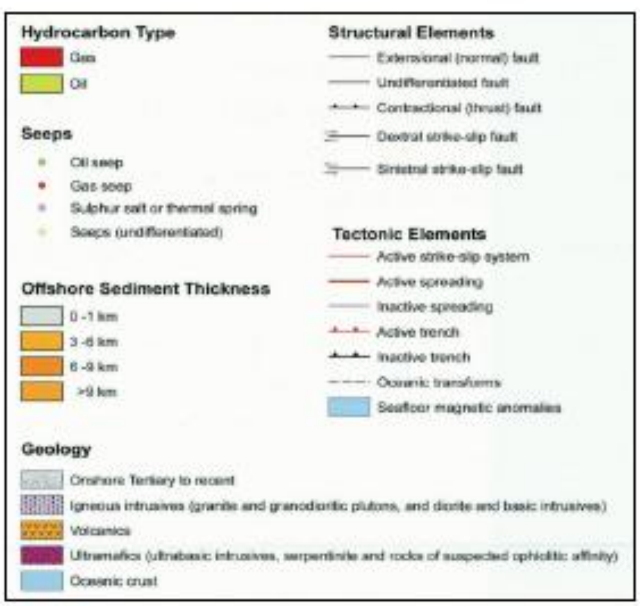


FIGURE 2: Surface geology, structural and tectonic elements, sedimentary basins and hydrocarbon occurrences of eastern Kalimantan and Sulawesi (Seapex, 2007)

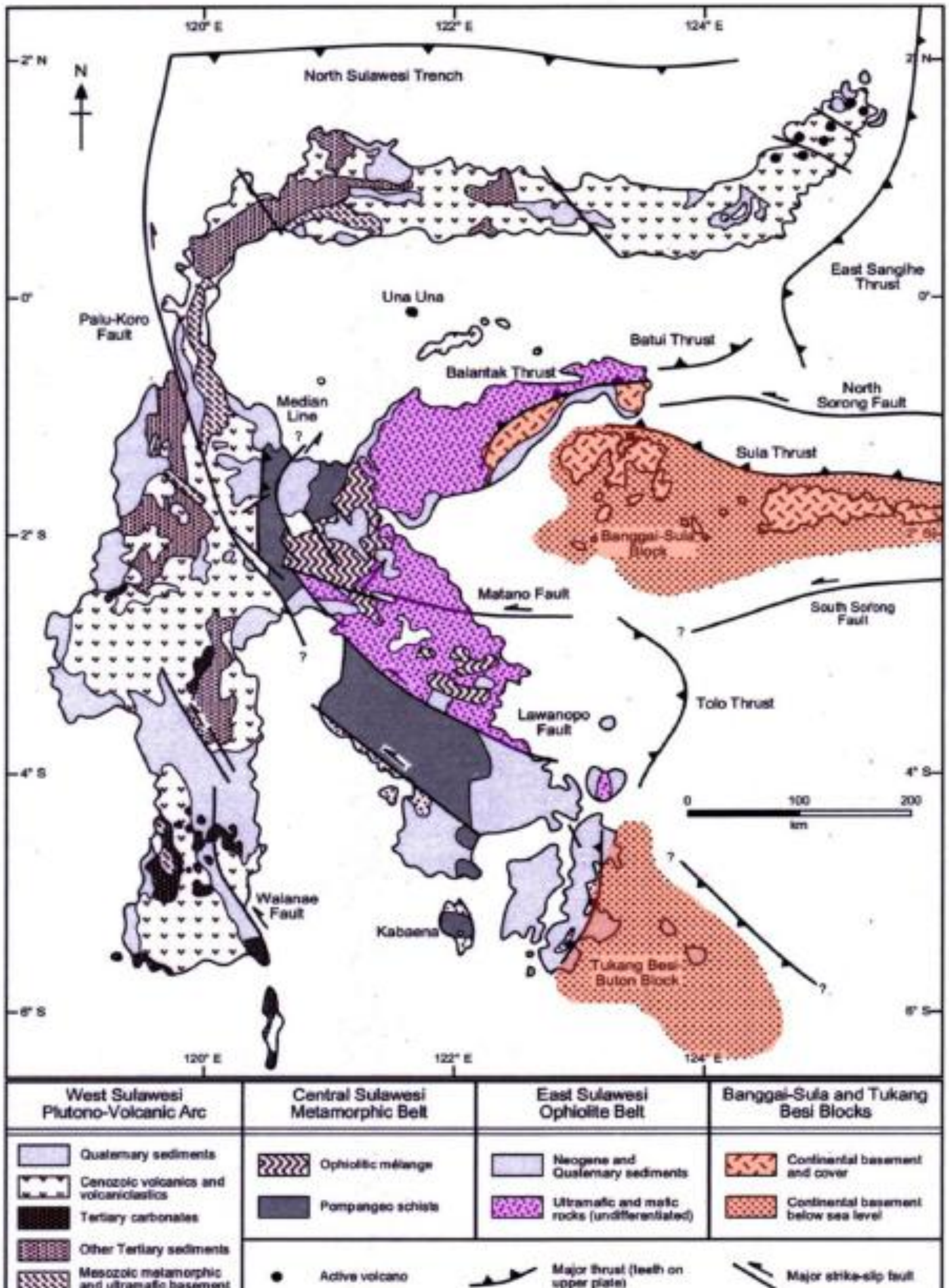
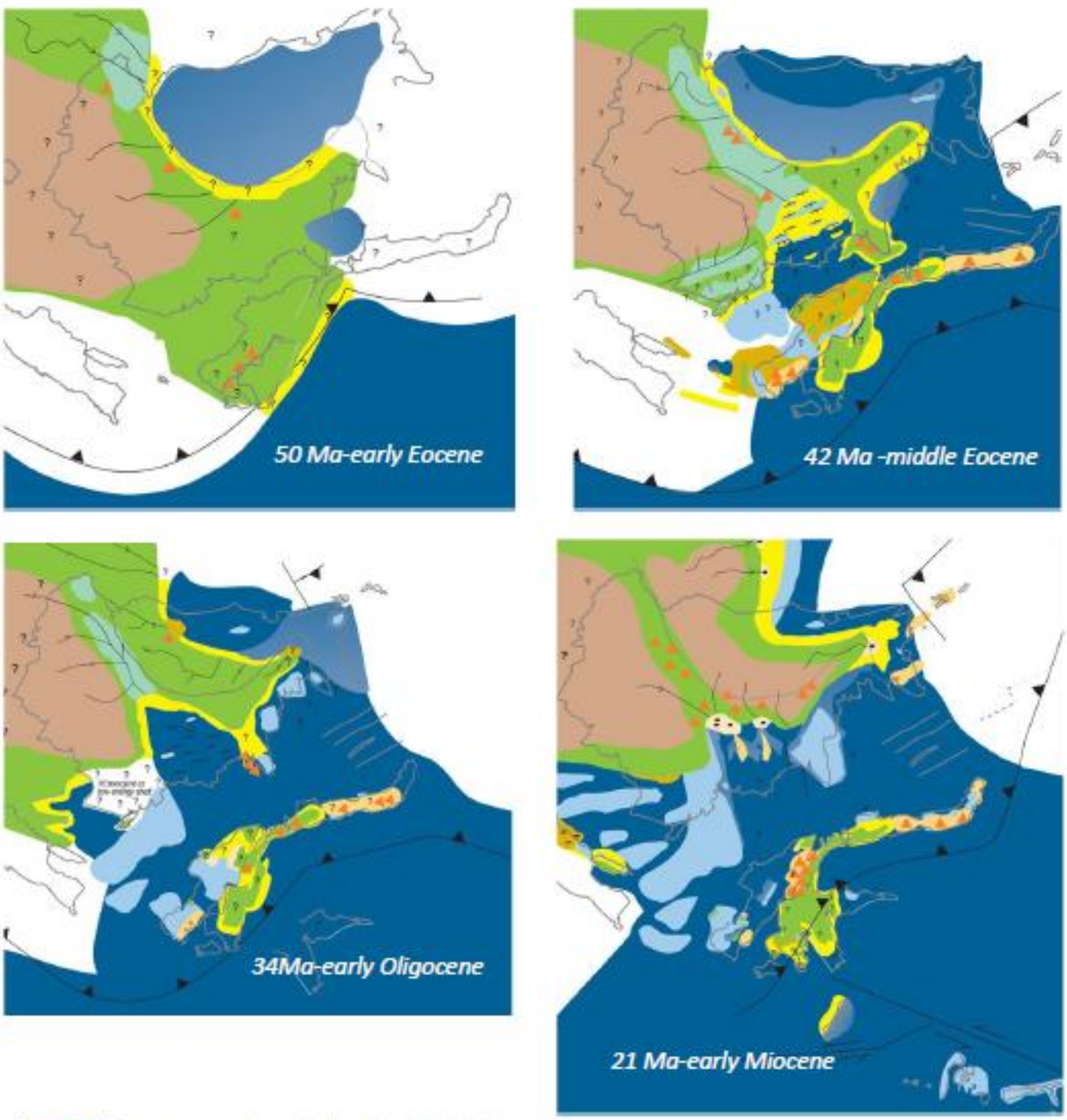


FIGURE 3: Geologic provinces of Sulawesi and adjacent islands (Moss and Wilson, 1998).



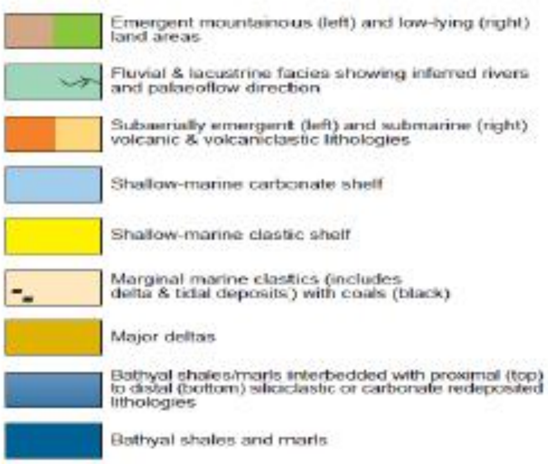
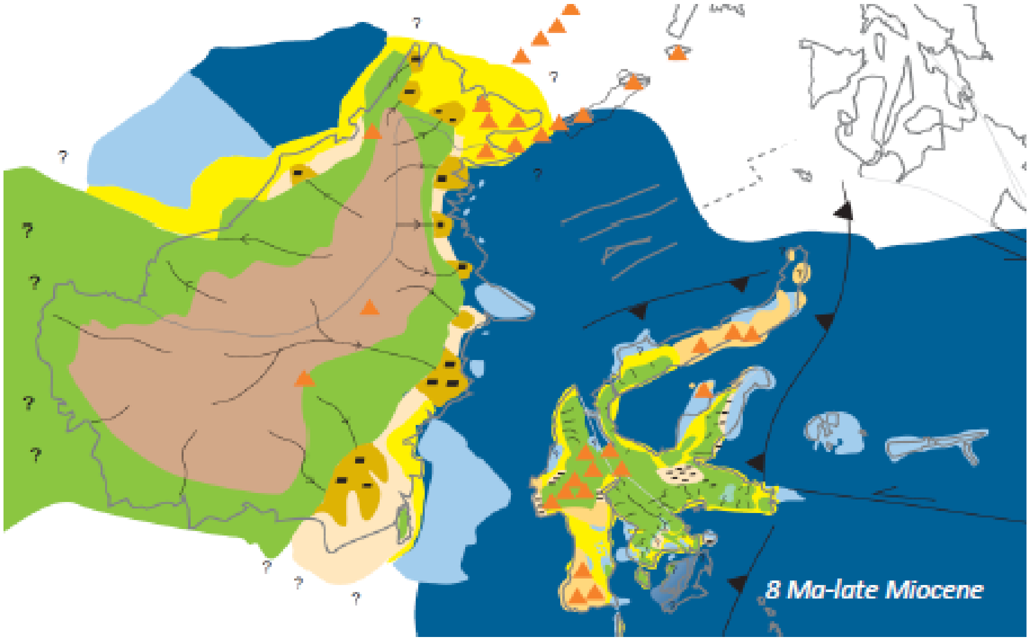
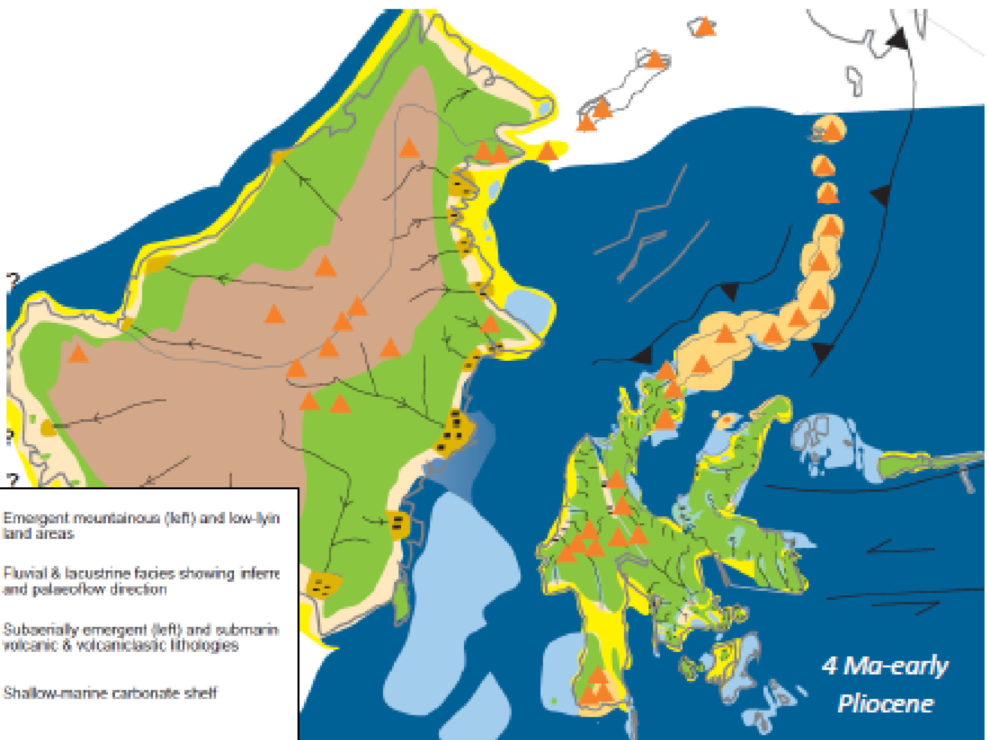


FIGURE 4: Palaeogeographic maps of Kalimantan and Sulawesi in Paleogene (Moss and Wilson, 1998). Note the change of environment from time to time and its implication to the presence of land area as island hopping or seas as barrier for faunal migration.





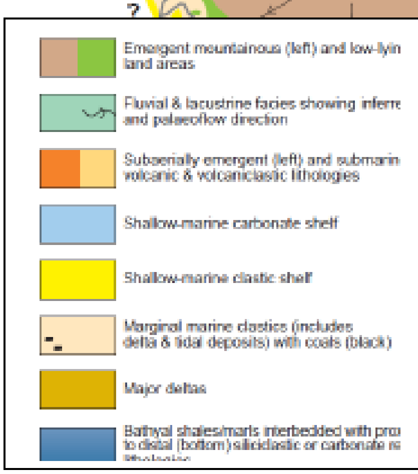


FIGURE 5: Palaeogeographic maps of Kalimantan and Sulawesi in Neogene (Moss and Wilson, 1998). Note the change of environment from time to time and its implication to the presence of land area as island hopping or seas as barrier for faunal migration.

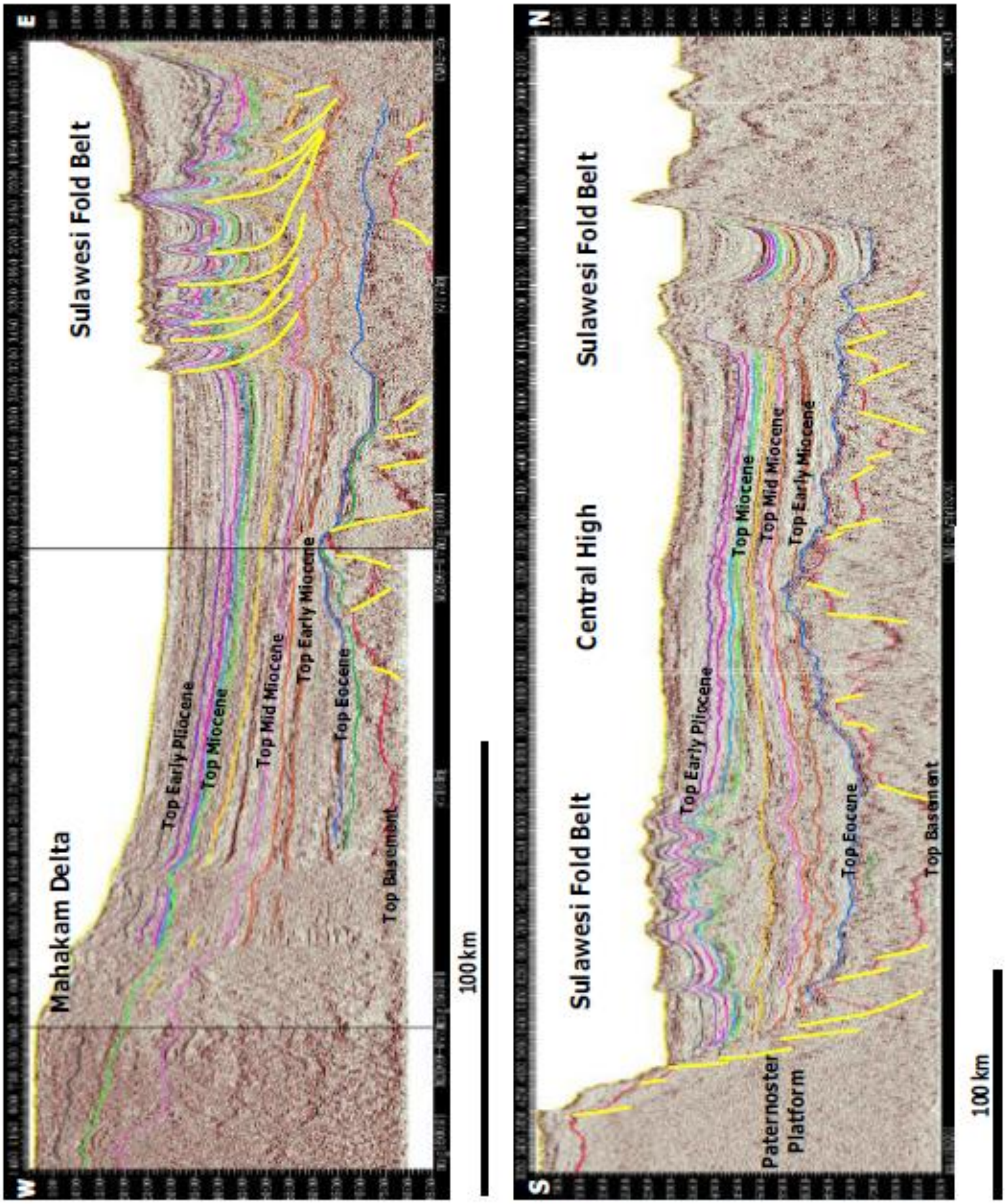
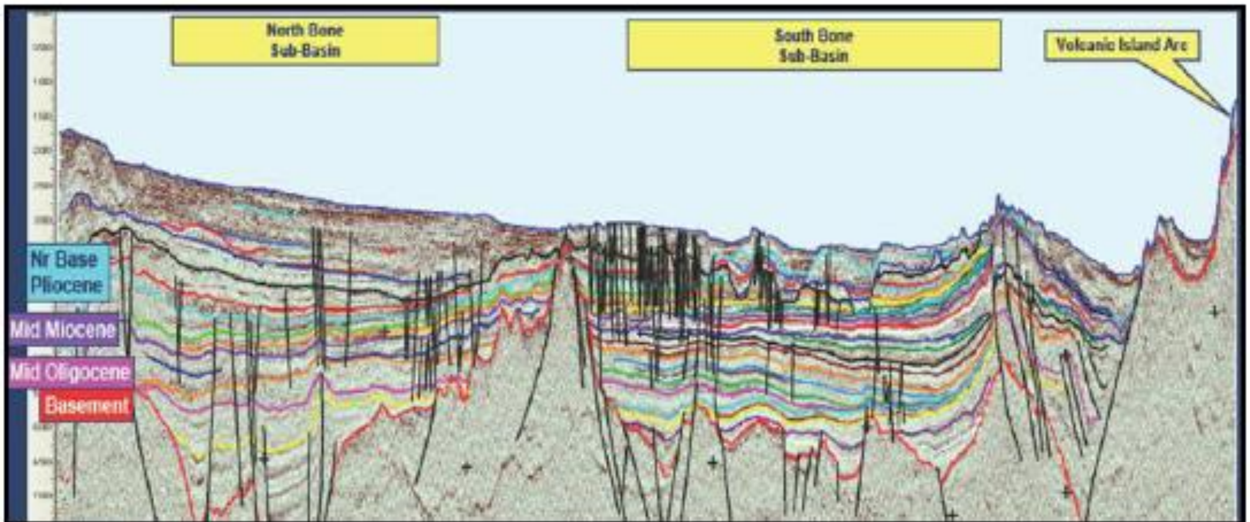


FIGURE 6: Seismic sections across the Makassar Straits. Note the presence of Paleogene rifted structures (horsts and grabens) and Neogene fold belt at west Sulawesi offshore (modified after Statoil Karama).



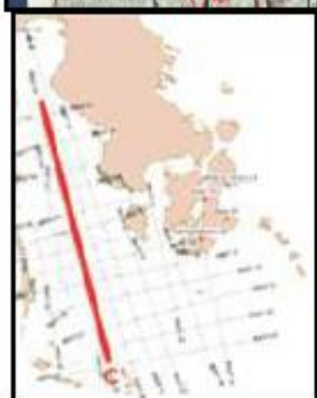
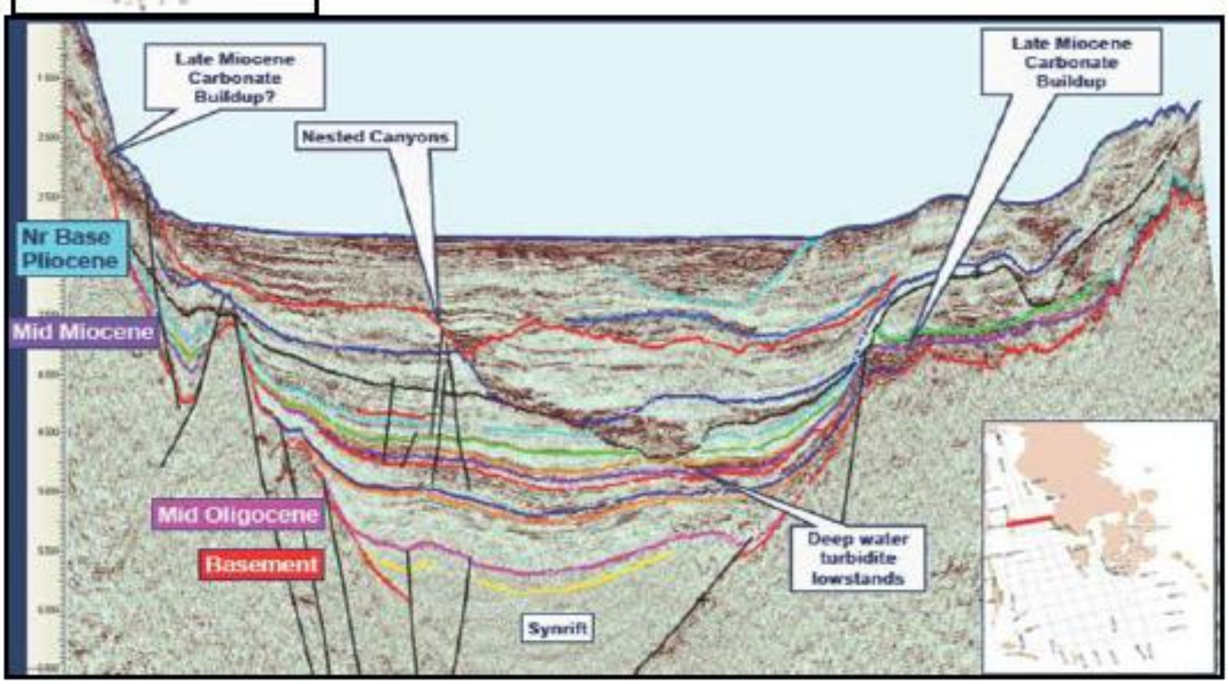


FIGURE 7: Rifted structures of Bone Basin.



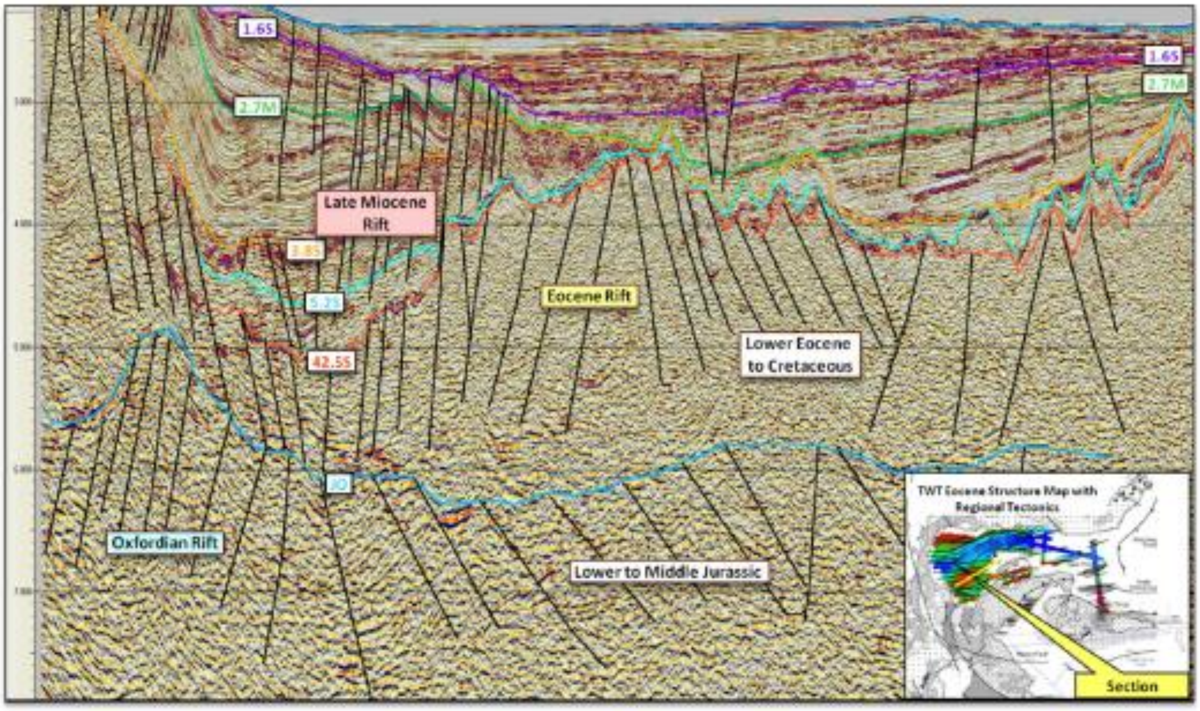


FIGURE 8: Rifted structures of Gorontalo Basin (Tomini Bay) showing a stack of Mesozoic and Tertiary rifts (Jablonski et al., 2007)).

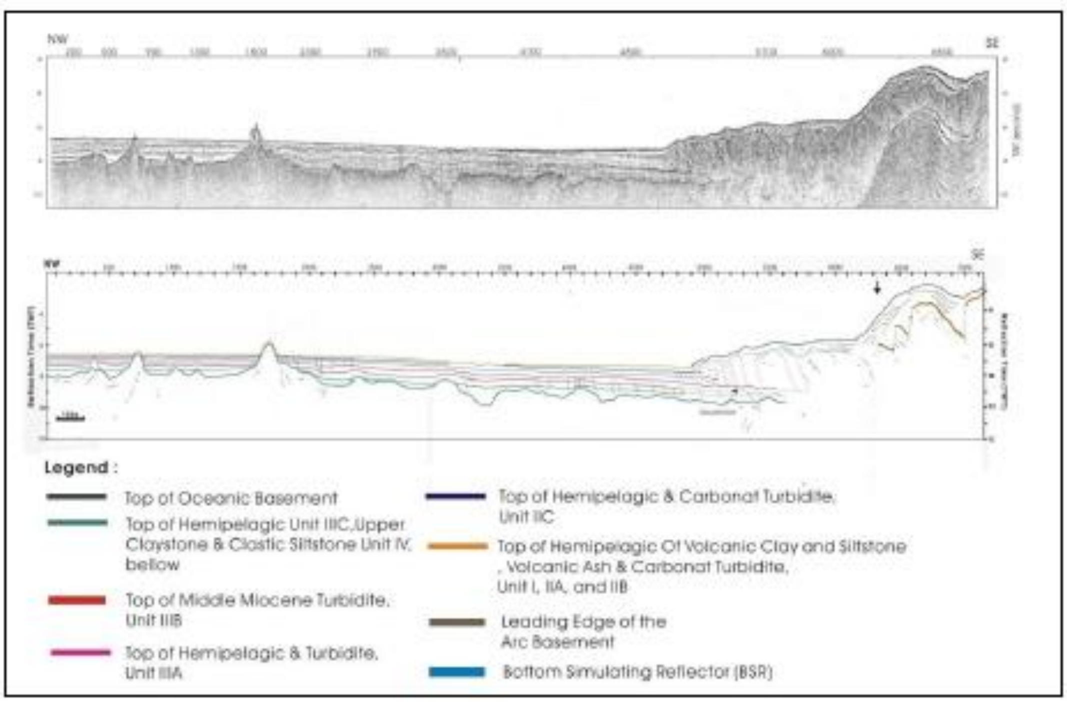


FIGURE 9: Seismic data acquired by geomarine survey at the Celebes/Sulawesi Sea. The basement is interpreted as oceanic crust (Djajadihardja et al., 2003). Compressive structures at SE are North Sulawesi foldbelt.

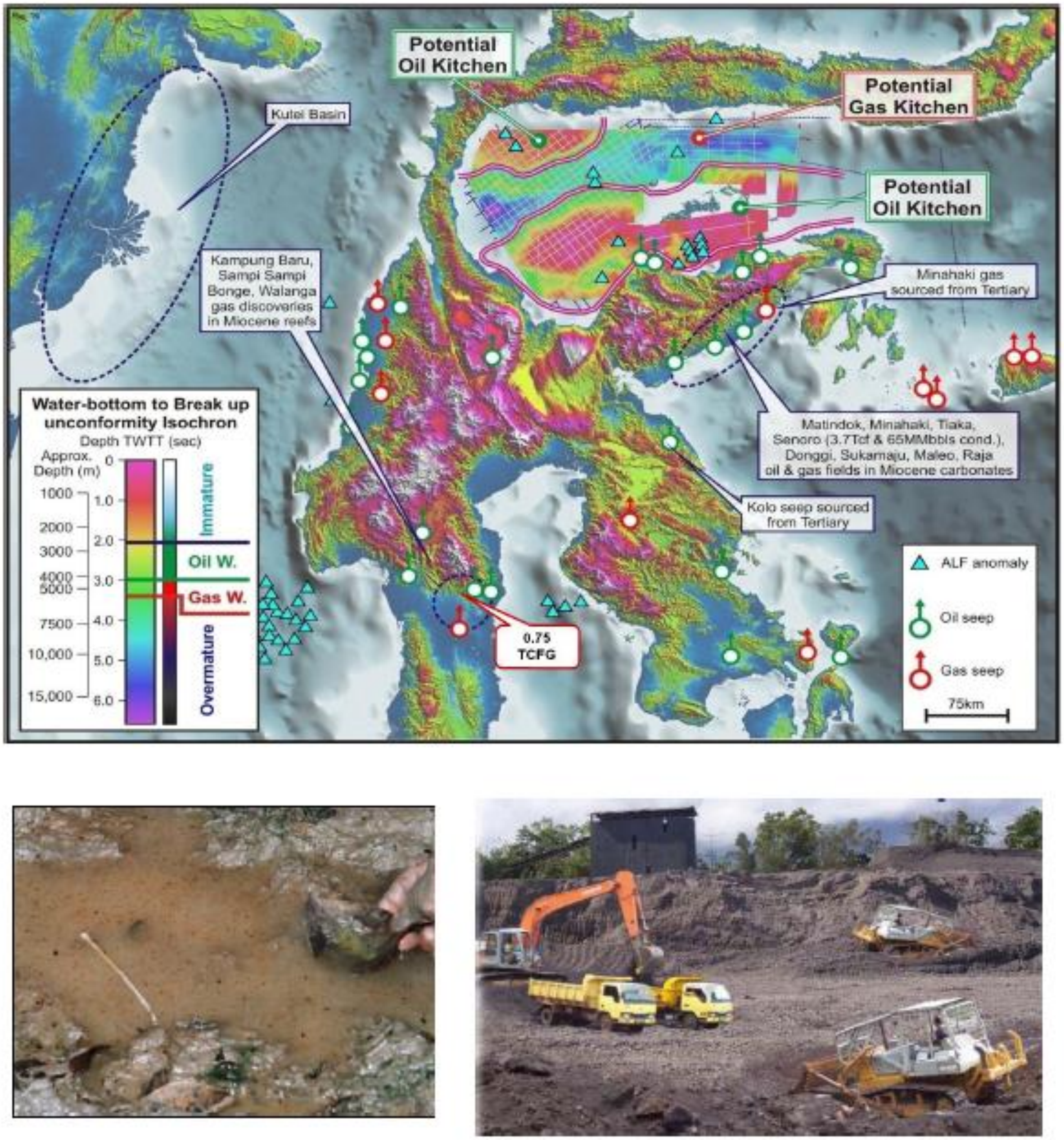
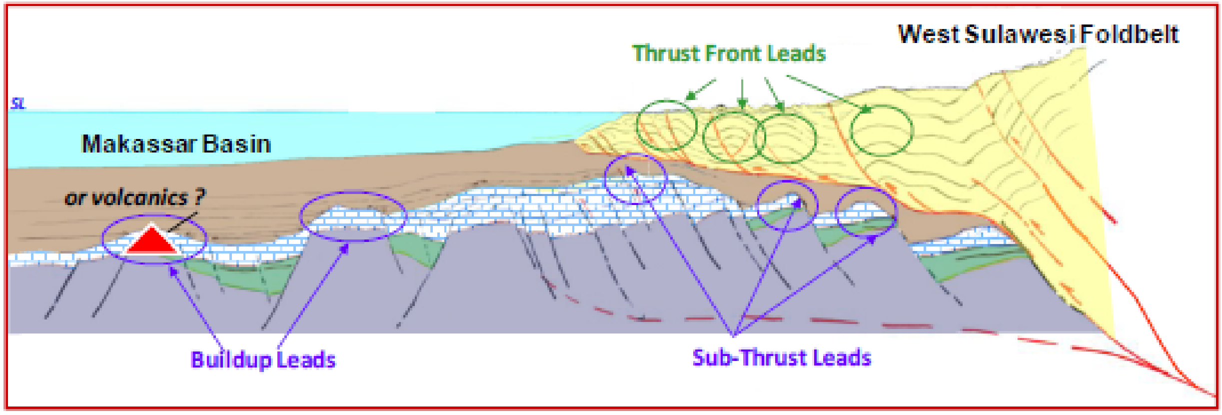


FIGURE 10: Hydrocarbon indications on and around Sulawesi and occurrences of oil and gas fields, ALF - airborne laser fluoroscence (Jablonski et al., 2007). Lower left figure shows oil seep at Bantaya area, western Sulawesi (after Tately Budong-Budong PSC). Lower right figure shows asphalt mine in Buton Island (after Japex Buton PSC).



Primary Play

- *Reservoir*: Oligocene – Miocene carbonate buildups on tilted fault-blocks
- *Source*: Eocene coals with potential lacustrine facies in grabens
- *Seal*: deepwater Oligocene-Miocene shales

Secondary Plays

- Eocene grabens
- Tertiary foldbelt
- Platform carbonate play
- Tertiary deepwater clastics

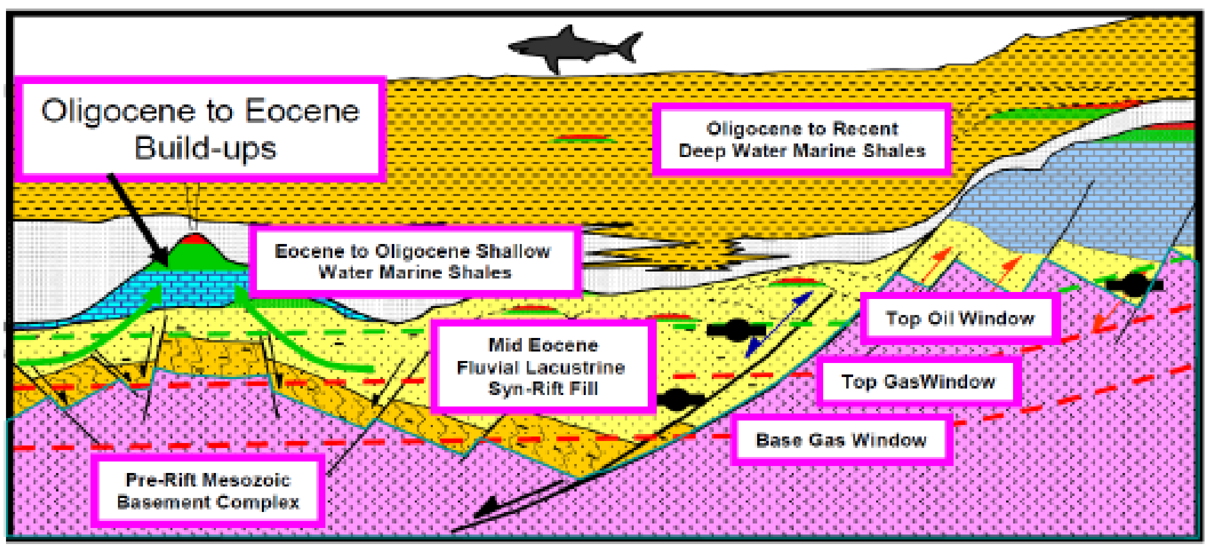


FIGURE 11: Schematic sections showing expected petroleum system and plays in west Sulawesi offshore, Makassar Strait. Several wells have been drilled by operators proving both volcanics and carbonates at horsts. The wells drilled to date are mostly dry, presence of Eocene sources in synrifts look the highest risk. Upper figure after ExxonMobil Surumana PSC, lower figure from Bacheller III (2011).

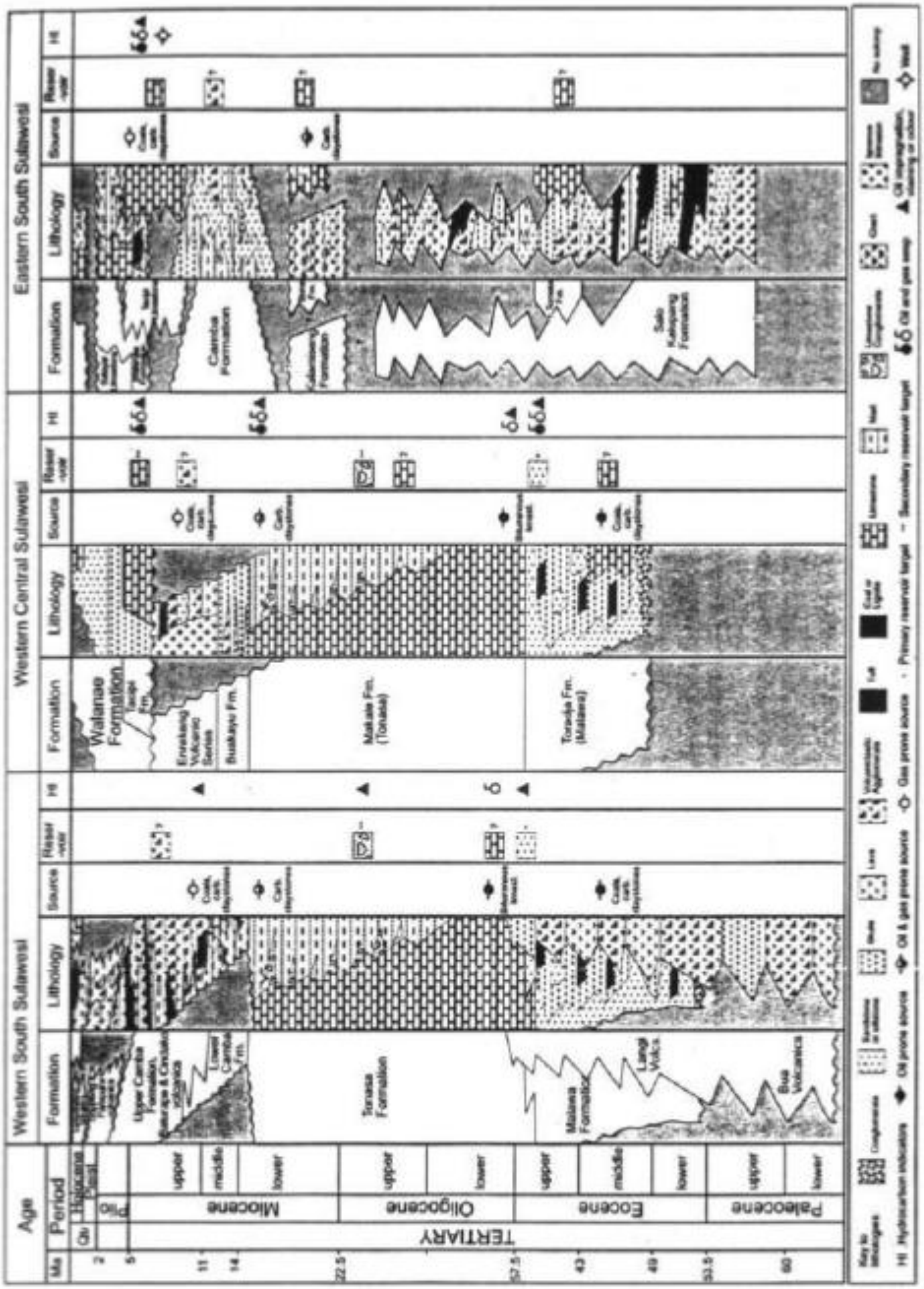


FIGURE 12: Stratigraphy of western and south Sulawesi, also showing elements of expected and interpreted sources and reservoirs as well as stratigraphic occurrences of hydrocarbon indications (Wilson et al., 1997).

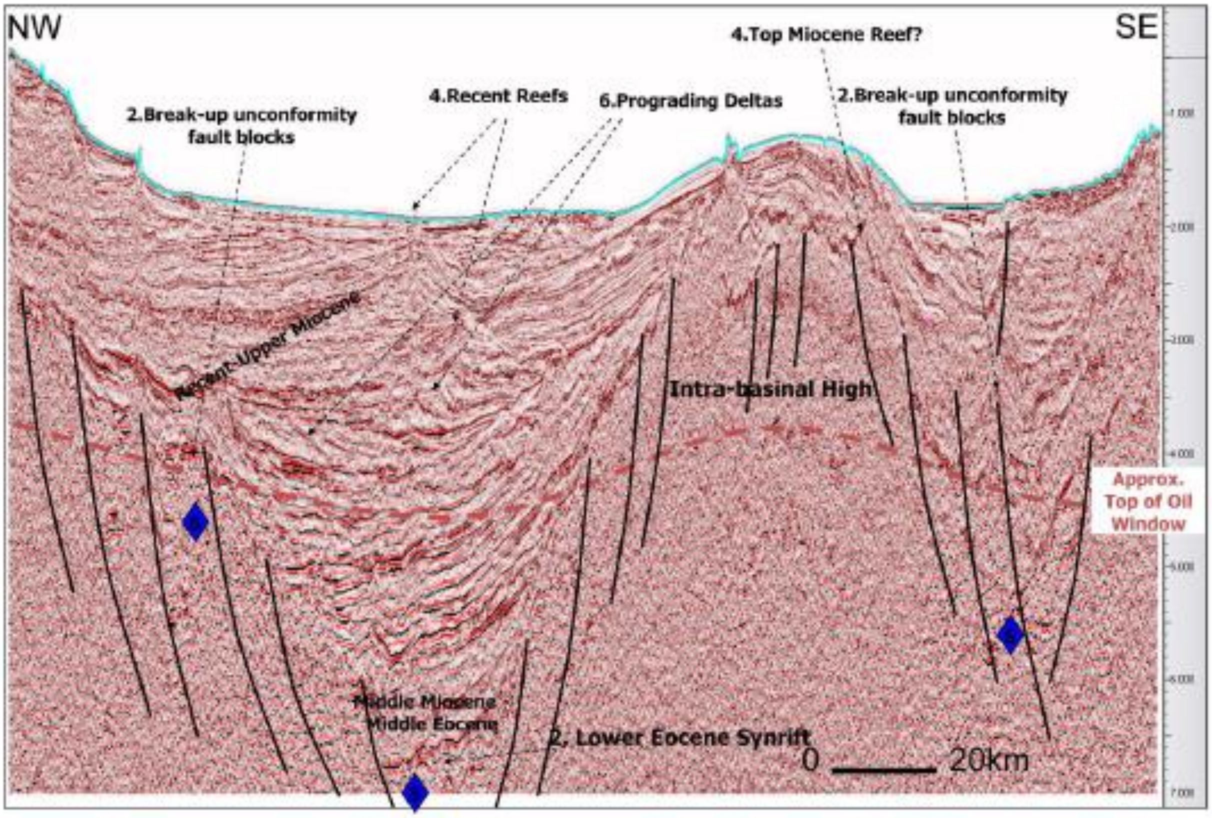


FIGURE 13: A seismic section in Gorontalo Basin, showing expected play types and petroleum kitchens (Jablonski et al., 2007)

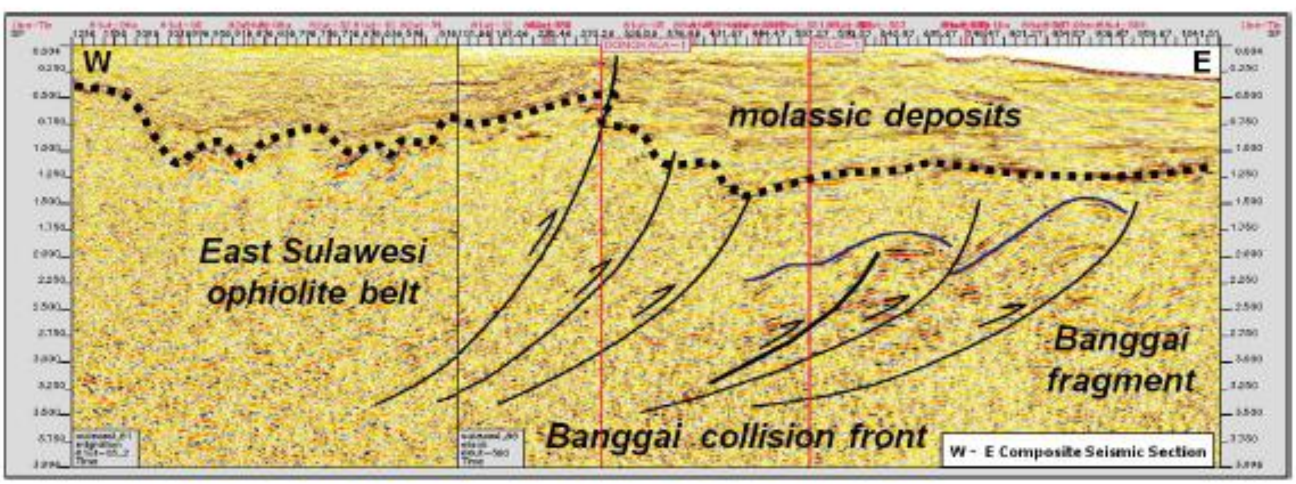


FIGURE 14: Seismic section across Banggai Basin, showing collision of Banggai terrane and East Sulawesi ophiolite. Fold and thrust belt exsists at the collision zone, deforming carbonate platform at the leading edge of the Banggai terrane, forming petroleum trap like Tiaka field. Molassic sediments were deposited after the collision and have become burial sediments to mature source rocks (Satyana, 2006).

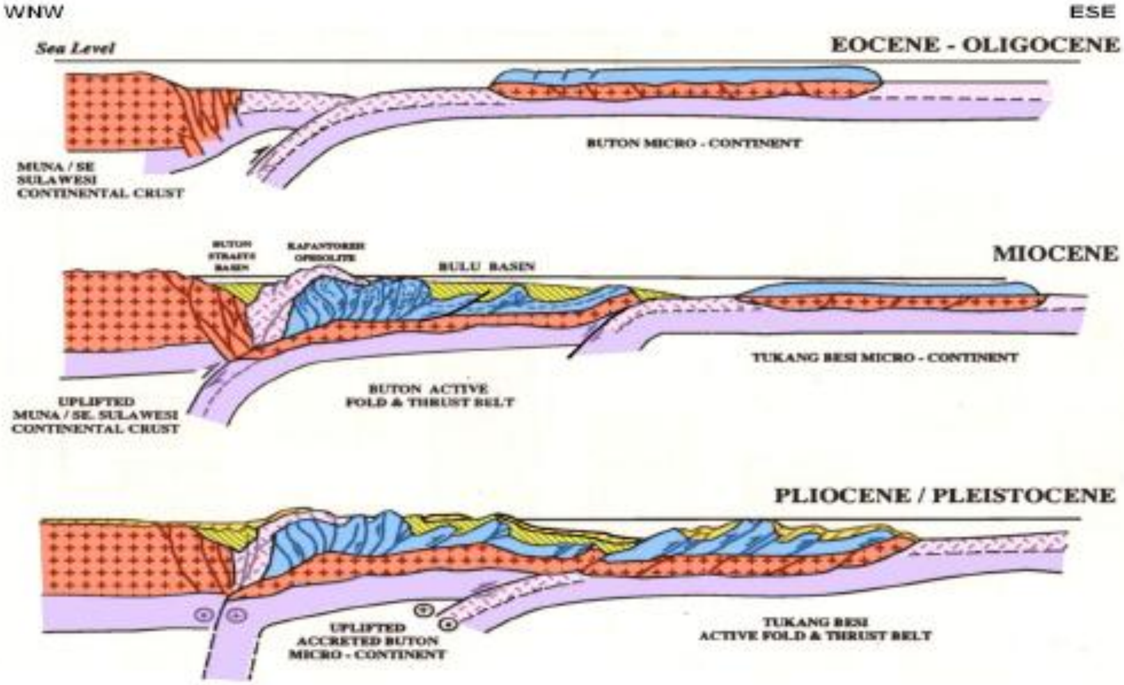


FIGURE 15: Schematic sections showing collision of Buton-Tukang Besi microcontinent with SE Sulawesi (Davidson, 1991). Satyana and Purwaningsih (2011) re-interprets that Tukang Besi did not collide Buton.

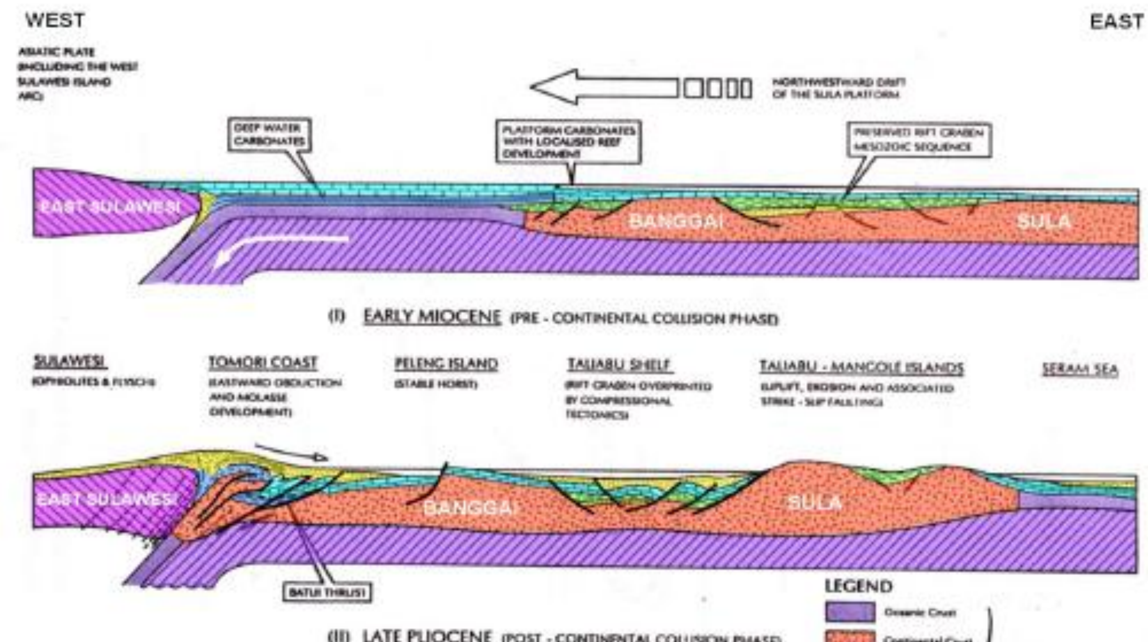


FIGURE 16: Schematic sections showing collision of Banggai-Sula microcontinent with East Sulawesi (Garrard et al., 1988).

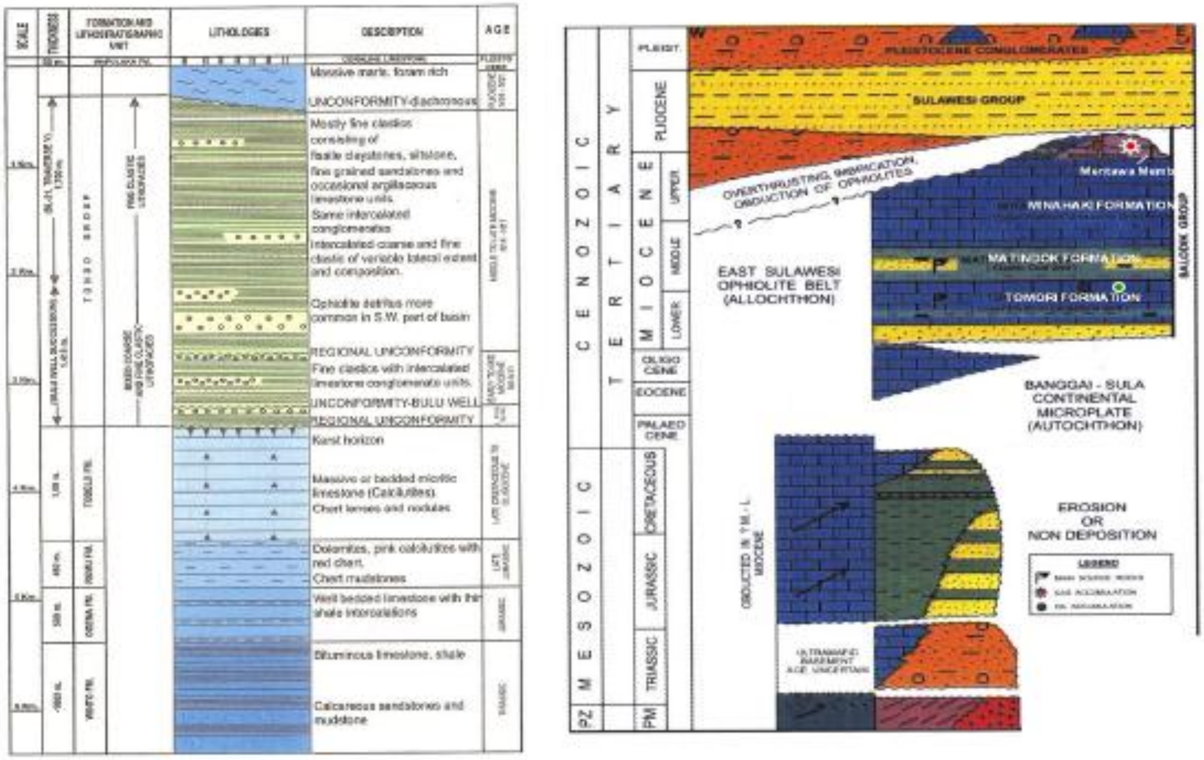


FIGURE 17: Stratigraphy of Buton (left, after Japex Buton PSC) and Banggai (right, Satyana, 2006), showing Mesozoic and Tertiary srata. Triassic Winto mudstones of Buton are proven source rocks. Proven sources of Banggai are marls and carbonates of Miocene Matindok and Tomori formations.

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)

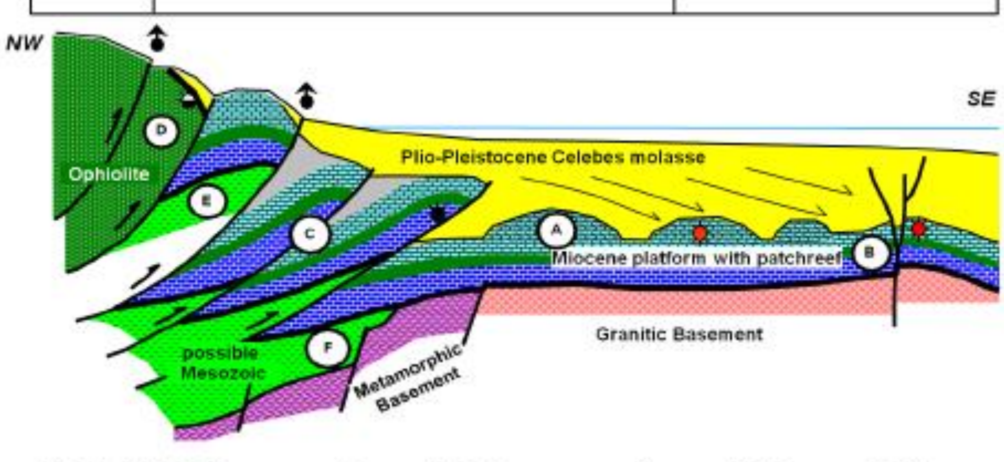


FIGURE 18: Play types of Banggai Basin, proven and potential (Satyana, 2006).