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TECTONICS, STRATIGRAPHY AND GEOCHEMISTRY OF THE MAKASSAR STRAITS: RECENT UPDATES FROM EXPLORING OFFSHORE WEST SULAWESI, OPPORTUNITIES AND RISKS

Awang Harun Satyana*
Shinta Damayanti*
Cipi Armandita*

ABSTRACT

The western part of the Makassar Straits is a very prolific petroleum province proved by the numerous oil and gas fields of the Lower Kutei-North Makassar Basin. These fields are found in the deltaic, shelfal and deep-water areas and are sourced and reservoired by a single petroleum system involving Miocene-Pliocene Mahakam deltaic sediments.

Its counterpart, the eastern part of the Makassar Straits or West Sulawesi Offshore, is very different from a petroleum geology perspective. The area has been under-explored and hence there is a lack of understanding. However, exploration activity in this area has been increasing significantly in the last five years. Several speculative seismic surveys have been acquired and working blocks have been established, operated by world-class operators. They have acquired detailed 2D-3D seismic data and other geophysical-geological data. Several expensive exploration wells have also now been drilled, mostly in the deep-water area.

The increase of exploration activity in West Sulawesi Offshore has enhanced our understanding but, it cannot instantly build a thorough knowledge of the petroleum geology of the area. There have been surprising results, both positive and negative, that were unexpected when compared with the prognoses for the wells drilled recently. It therefore appears that assessing the risk of both plays and prospects in this area is still difficult.

The Recent drilling results in West Sulawesi Offshore and South Makassar provide lessons in tectonics, stratigraphy and geochemistry for this area. For example the geotectonics of Western Sulawesi and the opening of the Makassar Straits affected Eocene source richness and sand or carbonate reservoir distribution. It has also been found that not every seismically low (deep) Eocene area is a source kitchen but it is has been proven that the Eocene is generating hydrocarbon in some areas, though the timing of hydrocarbon generation is critical for entrapped volumes. Also Neogene thin-skinned structures are now considered much more risky for source, reservoirs and hydrocarbon charging and sealing is another problem.

Integrated geologic-geophysical-geochemical (3G) evaluation, in accordance with post-drilling laboratory analyses, will improve the assessment of the opportunities and risks of exploring this challenging area.

* BPMIGAS

INTRODUCTION

The Makassar Straits, Central Indonesia, geographically divides Western Indonesia from Eastern Indonesia. Geologically, it was formed by rifting of the eastern margin of Western Indonesia or Sundaland as it is also known. This rifting separated the eastern most part of Sundaland namely the western part of Sulawesi.

Problems on the tectonics of the Makassar Straits, such as: how and when it was formed (by rifting or sea-floor spreading in Paleogene, Neogene or Quaternary), what basement underlies the straits (continental, oceanic, transitional), or rate of opening have been discussed and argued by many authors for around 35 years since Katili (1978) published his idea on the region related to the geotectonic position of Sulawesi. Some problems have been resolved and the explanations are now accepted by most authors such as: (1) the Makassar Straits were formed from the Paleogene to early Neogene, (2) the straits opened through continental rifting, or (3) the rate of opening is faster in North

Makassar compared to that of South Makassar. Other problems still remain unresolved.

The Makassar Straits today are deeper water areas in Indonesia. The depth ranges from a shelf edge of -200 m at the rim of the straits to -2500 m at its deepest point. The deep water areas of the western part of the Makassar Straits in North Makassar have been intensively explored for petroleum starting in the 1990s. This was a continuation of the exploration and production success achieved first in the Mahakam Delta to the Mahakam shelfal area where large to supergiant oil and gas fields have been discovered. Large and significant gas and oil fields have now been discovered in the deep water areas of the western Makassar Straits which are presently mostly under evaluation for development.

Its counterpart, the eastern part of the Makassar Straits or West Sulawesi offshore area has been under-explored compared to that of the western Makassar Straits. However, exploration activity in this area has been increasing significantly in the last five years. Several speculative seismic surveys have been acquired and working blocks have been established operated by world-class operators. They have acquired detailed 2D-3D seismic and other geophysical-geological data. Several exploration wells have been drilled, mostly in deep-water areas. The increase of exploration activity in the West Sulawesi Offshore has enhanced our understanding but, it cannot instantly build a thorough knowledge of the petroleum geology of the area and therefore the efforts have not yet been rewarded by significant success.

This paper will discuss our present knowledge of the tectonics, stratigraphy and geochemistry of the Makassar Straits, and their implications to the risks and opportunities for petroleum prospectivity in this region, mainly in the West Sulawesi offshore area.

METHODS

This paper will present a current discussion on the tectonics, stratigraphy and geochemistry of the Makassar Straits based on literature and regional activities conducted by companies working in this area. The paper will reveal the risks and opportunities working in this area. Published literature, unpublished data from studies, seismic and wells compose the interpretations outlined in this paper. All data are reviewed, analyzed, interpreted and synthesized to present an integrated explanation. Due to confidentiality issues, no raw data of seismic and wells will be published in this paper, except the data from already published literature.

RESULTS

Regional Tectonics of the Eastern Sundaland

Being originally a part of eastern Sundaland, the tectonics of the Makassar Straits should be evaluated as part of Sundaland's tectonic history.
Having been an active continental margin since the Jurassic, Sundaland has a history of growing and slivering of a continent by accretion and dispersion, respectively (Satyana, 2003, 2010a). It is composed of a number of terranes which came from northern Gondwanaland (Metcalfe, 1996), drifted separately, assembled, and accreted forming Sundaland. The terranes composing Sundaland are: Sibumasu (formerly called Mergui and Malacca), East Malaya, Indochina, Southwest Borneo (partly called Schwaner), Semitau and Paternoster-Kangean. Later dispersion of eastern terranes broke the assembly and slivered Sundaland. Starting at around 50 Ma, in the Middle Eocene, some of the accreted mass of SE Sundaland dispersed through rifting and drifted eastward and southeastward, leaving rifted structures of Eastern Sundaland presently located at the Makassar Straits, East Java Sea, Gorontalo Bay and Bone Bay (Satyana, 2010b).

The history of dispersion and rifting of Eastern Sundaland is complicated and there are a number of mechanisms proposed by authors for the rifts of Eastern Sundaland (Satyana, 2003, 2010b), involving: (1) crustal breakdown to the west of the South Sulawesi volcanic arc by Plio-Pleistocene diastrophism, (2) back-arc spreading of marginal basins of Southwest Pacific areas, (3) rotation of continental Southeastern Sundaland, (4) back-arc spreading due to subduction rollback related to India-Eurasia collision at 50 Ma, (5) southern extension related to sea-floor spreading of the Sulawesi Sea, (6) tectonic escape due to India-Eurasia collision and (7) mantle delamination by upwelling plume under Eastern Sundaland.

The eastern margin of Sundaland is fragmented and tectonically very complicated. The accreted rocks comprise variably metamorphosed accretionary complexes, imbricated terranes, melange, turbidite and broken formations, and ophiolites. These rocks have suffered considerable dismemberment, tectonic and structural modification, and thermal overprinting due to tectonic and metamorphic activity throughout the Tertiary, related to the convergence of the Indo-Australian, Eurasian and western Pacific microplates (Parkinson et al, 1998). The provenance and way of dispersion of some fragments believed to be once parts of Eastern Sundaland are also complex and variably interpreted.

Physiography of the Makassar Straits

The Makassar Straits are a north-south orientated seaway, around 600km long, 100-200km wide with water depths greater than 2000m (Moss et al., 2000). Bathymetrically the Makassar Straits are subdivided into northern and southern depressions and are hence sometimes referred to as the North and South Makassar Basins (Figure 1).

The western side of the North Makassar Straits depression is bordered by a wide shelf (<200m water depth) area up to 50km wide before sloping down to depths greater than 2000m (Figure 1). This wide shelf is the result of outbuilding of the proto-Mahakam delta from approximately 15 Ma to the present day. Sited upon the wide shelf area bordering the western side of the North Makassar Straits Basin is the present-day location of the Mahakam delta. In contrast, the eastern margin of the north Makassar Straits depression is defined by a narrow (generally 10-20km wide) shelf bordering Central Sulawesi which sharply drops off to depths greater than 1000m before more gradually sloping down to depths greater than 2000 m. The southern margin of the North Makassar Straits Basin is well defined bathymetrically by the relatively steep NW-SE trending northern edge of the Paternoster Platform. The Paternoster Platform is a wide area of shelf with water depths generally less than 200m. The northern margin of the North Makassar Straits Basin is less well defined but is generally drawn along the WNW-ESE trending bathymetric promontory called the Mangkalihat Arch (southeast of the Mangkalihat Peninsula) and the narrow shelf offshore from the neck of the north arm of Sulawesi.

The South Makassar Strait/Basin (up to 2000 m water depth) is separated from the North Makassar Strait by the major Adang-Paternoster strike-slip fault trending WNW-ESE from north of the Paternoster Platform to South Sulawesi. The western part of the South Makassar Basin is occupied by shelfal area underlain by Paternoster Platform. To the east, the basin is bordered by another platform called the Spermonde Shelf, therefore, the area of basin is much more limited compared to that of the North Makassar Basin. The narrow channel called Labani connects the South Makassar Basin to the North Makassar Basin. To the south, the South Makassar Strait shoals into the shallow water East Java Shelf. Rifting arms of the southern Makassar Strait extended southwest- and southward into the East Java Sea Basin where rifted structures are found comprising horsts and grabens trending SW-NE.

Basement and Deformation of the Makassar Straits

Eastern Kalimantan and Western 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. There has been debate about the age of formation of the straits between Neogene and Paleogene. An 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. Figure 2 shows regional seismic lines across the Makassar Straits. Its schematic deformation is shown at Figure 3.

The mechanism of the opening has also been the subject of controversy. Most authors have favored an extensional origin for the straits. Rift development during the opening of the Makassar Straits, from the middle Eocene to early Oligocene, appears to have been strongly affected by the presence of a series of throughgoing basement faults that cut across Borneo and through Sulawesi in northwest-southeast and north-northwest–south-southeast orientations (Gartrell et al., 2005). At a regional scale, the northern and southern Makassar basins are offset in a left-lateral sense across the Adang-Paternoster basement fault zone.

Situmorang (1982) provided an evaluation of the opening of the Makassar Straits based on subsidence history and he concluded that formation of the basin started with rifting in Lower-Middle Eocene or probably earlier, and continued until the Lower Miocene. Rifting had ceased by the end of Lower Miocene, and since then the sediments have been deposited continuously across the basin without significant deformation. Multichannel reflection seismic data from the basin indicate that deposition of the sediments has occurred at a uniform rate while the basin itself was subsiding uniformly, which resulted in deposition of more than 6 km of sediments during the Tertiary. The stretching model also predicts that oceanic crust will occur at a stretching factor of 2.9, corresponding to a present water depth of not less than 3.2 km. Since such a depth of water does not occur in the basin, it is believed that sea-floor spreading margins have not yet been developed in the Makassar Basin. The Basin is underlain only by a thinner continental crust compared with the surrounding areas.

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/thinned continental crust (due to rifting) 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 more difficult to determine. There have been arguments 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 and, gravity-magnetic models and seismic data show variable interpretations hence complicating the matter. Further discussion on the nature of the basement of North Makassar Strait can be found in a recent paper by Hall et al. (2009) but, this publication did not resolve the question. The disagreement is likely to continue among those working in the area. However, a recent well drilled in the North Makassar Basin, Rangkong-1 (Exxon, 2009) in the Surumana Block encountered altered volcanic basement rocks, petrochemically showing a definite association with continental crust (Bacheller III et al., 2011).

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 a 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. The foldbelt is mapped as compressional folds over a thin-skinned detachment within probably over-pressured, late Eocene to early Miocene mudrocks. The West Sulawesi Fold Belt, occurs both onshore and offshore western Sulawesi. The northern portion of the foldbelt is imbricated, possibly related to thick-skinned, basement-cored detachment over former, late Eocene, oceanic crust, while the southern portion comprises a series of large anticlines, soling out on a thin-skinned, basal detachment within mobile Eocene-Oligocene shales.

From south to north, the Offshore West Sulawesi Foldbelt can be divided into three provinces (Puspita et al., 2005, Figure 2): the Southern Structural Province (SSP), Central Structural Province (CSP) and Northern Structural Province (NSP) based on seafloor characteristics, subsurface deformation and 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 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 mounds. Recent wells in the North and South Makassar Straits show the presence of both volcanic mounds above a horst (Rangkong-1, Exxon 2009) and carbonate build-ups (Sultan-1, Exxon 2009, Romeo-1 and Bravo-1, both operated by Marathon, 2010) (Bacheller III et al., 2011; Armandita et al., 2011).

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.

Stratigraphy and Paleogeographic Evolution

Western Sulawesi and the Makassar Straits are generally considered to be the easternmost edge of the Sunda Craton, a region of Mesozoic continental crust extended to varying degrees in the Paleocene to Lower Eocene. It is overlain by a sequence of Tertiary clastics, carbonates and volcanics affected by complex and controversial tectonics as the Australian-Indian, Pacific and Southeast Asian micro-plates interacted.

Figure 4 shows the tectonostratigraphy of the region. Figures 5-8 show the paleogeographic evolution of the region which is important for predicting the development of petroleum sources, reservoirs and seals through geological time.

There is a significant difference in the stratigraphy of the North Makassar Basin and the southern one, mainly in the Neogene sequences. The difference is caused by the different provenances of the very large volumes of sediment in East Kalimantan (from Borneo via the Mahakam Delta) and West Sulawesi (the volcanic foldbelt). These provenances greatly affected the Neogene stratigraphy of the North Makassar Basin, which was not the case for the South Makassar Basin.

The opening of the North Makassar Straits in Lower Paleogene resulted in rifted structures comprising grabens and horsts as indicated on seismic sections. Classical tectonostratigraphic division applied to basins of Western Indonesia is applicable here. Pre-rift rock units mainly consist of Paleocene to Lower Eocene and older volcanics and volcaniclastics/epiclastic sediments as penetrated by the Rangkong-1 well (ExxonMobil Surumana, 2010; Bacheller III et al., 2011). Early syn-rift nonmarine sediments of lacustrine and fluvio-deltaic facies were presumably deposited within the grabens. Subaerial horsts at that time are considered to source the sediments. Based on regional stratigraphy, these sediments could be middle-upper Eocene in age and will be transgressive in nature as circum-Sundaland basins display. They consist of siliciclastic sediments from shallow lacustrine facies, through inner and outer neritic, up to upper bathyal. The main and late syn-rift sediments are probably transitional, deltaic and shallow marine and are thought to have been deposited in every graben of the North Makassar Basin. No well in the basin has penetrated this section therefore we do not know its actual stratigraphy.

During the Late Eocene to Early Miocene, the North Makassar Basin continued to open and submerged resulting in post-rift sediments mainly consisting of carbonates and fine-grained sediments (Figures 5-6). The Oligocene in the basin was a sag phase with extensive carbonate shelves and platforms and with a starved basin in the center. Reefal carbonates grew in this period selectively on horst blocks or high areas in shallow water where siliciclastic inputs were minimal.

Starting in the Neogene, the North Makassar basin's stratigraphy was dominantly affected by sediments derived from a provenance in Eastern Kalimantan where deltaic sediments were deposited in the shelfal to deep water area of the western North Makassar Strait and also from Western Sulawesi where volcaniclastic sediments were deposited from the shelf to deep water area in the eastern North Makassar Strait (Figures 7-8). This period was coeval with compression and inversion in central Kalimantan, providing a large source of clastic sediments that were carried into the Makassar Straits, and was also coeval with volcanism in Sulawesi.

Vast amounts of deltaic sediment (>10 km thick) were deposited in the Kutei Basin from the early Miocene to the present (Figures 6-8). Substantial eastward (basinward) progradation pushed shelf edges to near their easternmost positions by the end of the Miocene. North of the Mahakam delta, the terminal shelf edges of Pliocene and Pleistocene cycles have been stepping back landward, apparently because of (1) a decrease in clastic sediment supply and (2) rapid subsidence (both regional and fault related) (Saller et al., 2006). In contrast, terminal shelf edges in the central and southern part of the basin remained in the same approximate geographic location during the Pliocene and Pleistocene. Beneath the present mouth of the delta is the centre of the Mahakam depocenter where there is an estimated sediment thickness of more than 14 km. The current deep-water part of the Kutei Basin/North Makassar Strait has been in a deep-water depositional environment since the late Oligocene.

In West Sulawesi Offshore, the Mesozoic basement consists of metamorphic rocks unconformably overlain by less deformed Upper Cretaceous dark shales and volcanic rocks (Hall et al., 2009). These are at least 1000 m thick and considered laterally equivalent to basement in other parts of western Sulawesi. They are interpreted to be the deposits of a forearc basin situated to the west of a west-dipping subduction zone (Hasan 1991), or a passive margin (Hall et al., 2009). Non-marine sediments at the base of the lower Cenozoic sections could be as old as the Paleocene, but the oldest dated sediments are marine and record a transgression in the Middle Eocene that must post-date the initiation of rifting in the region. The Eocene sediments were deposited in graben and half-grabens in both marginal marine and marine environments. The post-rift subsidence phase had started by the Late Eocene. In the Late Eocene carbonate shoals and shelf mudstones developed on both margins of the Makassar Straits and, by the end of the Oligocene, most of West Sulawesi was an area of shelf carbonate and mudstone deposition. The lowermost Miocene has not been found, but there is little evidence in West Sulawesi for either a significant regional unconformity, or input of orogenic sediment. Instead, throughout the Early Miocene and in places until the Middle or Late Miocene, carbonates and mudstones were deposited on a shallow-marine continental margin. Further south, in the south arm of Sulawesi there is no evidence for a significant break in marine deposition. Only during the Pliocene did the character of sedimentation across the whole of western, central and eastern Sulawesi change significantly. Uplift and erosion was followed by the deposition of coarse clastics derived from an orogenic belt to the east. To the west of the orogenic belt there was syn-orogenic sedimentation, inversion and folding above Paleogene half-graben, detachment folding and thrusting, and the development of intra-basinal unconformities and mini-basins, which has propagated west into the Makassar Straits. In the Pliocene the character of sedimentation changed significantly. Uplift and erosion was followed by the deposition of coarse clastics derived from an orogenic belt. The Paleogene half-graben were inverted, there was localized detachment folding and the overlying Neogene section was folded, faulted and eroded in places. Contractional deformation in western Sulawesi dates from the Pliocene, whereas in eastern Kalimantan it dates from the Early Miocene (Calvert and Hall, 2007).

Several recent wells have been drilled in the eastern part of the Makassar Strait revealing the actual stratigraphy of the region. Bacheller III et al. (2011) and Armandita et al. (2011) reported the stratigraphy of the Surumana, Mandar and Pasangkayu Blocks penetrated by several recent wells (Exxon, 2009-2010; Marathon, 2010-2011). Well Rangkong-1 reveals the actual stratigraphy of one part of the Surumana Block. The shallow section is distal turbidite fans deposited in an upper to middle bathyal setting from Recent to Middle Miocene (foram zone N19-N6). This overlies a highly condensed, but continuous, succession of upper to middle bathyal, calcareous mudstones, ranging in age from Early Miocene to Early Oligocene (foram zone N6-P21). This condensed section overlies 2 meters of carbonate deposited in deepwater, based on abundant planktonic and diagnostic deepwater benthic forams. The Eocene to Oligocene boundary seems to occur in or just above this carbonate based on the first down hole occurrence of Eocene planktonic forams (*Hantkenina* spp., T. *cerroazulensis*). The carbonate layer was deposited on highly altered (zeolites primarily), vesicular volcanics which seem to become less altered and vesicular with depth. The age of the oldest sedimentary rocks overlying unaltered volcanics could be as old as latest Middle Eocene (foram zone P15, with rare *Truncorotaloides* spp.). Geochemical analyses on the volcanics indicate a borderline andesitic-dacitic composition and a calcalkaline, continental arc signature or subduction-related. Rangkong-1 missed the target of a carbonate build-up, but in other parts of the Surumana Block the build ups could be developed as recent gravity-magnetic study has indicated.

The Sultan-1 well was drilled in the Mandar Block at the northern end of the South Makassar Basin. The Sultan prospect consisted of about five carbonate pinnacles rooted on a large carbonate platform (Bacheller III et al., 2011). The well encountered Late Miocene deep-water shales on a 389 m thick sequence of Middle Eocene to Late Oligocene carbonates sitting on older, non-marine pyroclastic volcanics. Another well drilled later in this block, Kris-1, encountered Late Oligocene deep-water shales on 121 m of Middle to Late Eocene carbonates, characterized by dolomitized larger benthic forams (foram zone Tb), red algae and skeletal packstone. This succession is sitting on Middle Eocene clastics (foram zone Ta3) underlain by volcanic basement.

Bravo-1 (Marathon Pasangkayu, 2010) in North Makassar penetrated middle bathyal to outer neritic early-late Pliocene sediments which unconformably overlaid middle to late Eocene carbonates of a middle to outer neritic depositional environment. Deep-water turbiditic sediments of Pliocene to Pleistocene in age were also penetrated by the Romeo-1 well (Marathon Pasangkayu, 2010) (Armandita et al., 2011).

Generally, it seems that in the Makassar Straits the degree of extension, related subsidence rates and sea-level fluctuations combined to produce a favorable environment for high relief Oligocene buildups as well as lower relief Eocene platform carbonates. The distribution of Eocene carbonates was also controlled by paleo-water depth primarily related to the amount of extension and related subsidence.

Petroleum Geochemistry

Source rock development in the basin depended on the tectono-stratigraphic framework. The Rifting of the Makassar Strait led to the development of grabens and horsts. Horsts became the provenances of sediments deposited within adjacent grabens as source, reservoir, or sealing rocks. Opening of the grabens, especially if the floors of the Makassar Straits are thinned continental crust, provided an opportunity for development of lacustrine environments good for source rock development. Predicting the development of source facies in this area can use a series of paleogeographic maps (Figures 5-8).

In the western North Makassar Basin, within the shelfal and deep-water areas of the Kutei Basin, knowledge of the petroleum geochemistry based on oil and rock analyses has been firmly established. The majority of hydrocarbon accumulations in these areas can be correlated to the Miocene deltaics (Lin et al., 2005). Two main episodes of coal and carbonaceous shale deposition are observed in association with the development of the ancient Mahakam Delta. One episode occurred in the mid-Miocene, and the other commenced in the upper Miocene (ca. 8 mybp) which continues today. Very limited oil and gas condensate accumulations suspected of being sourced from the Eocene syn-rift and Oligocene marine carbonates are also known at the basin margins.

The geochemical analyses indicate that allochthonous land-plant organic matter is the source of hydrocarbons in the deepwater Kutei Basin (Lin et al., 2005). The organic matter in turbidites is dominated by plant leaf fragments (occurring as thin coaly laminae), woody debris and less frequently resin bodies and recycled coaly particles. TOC contents can range from 1 to over 50% with hydrogen indices mostly between 100 and 400 (mg HC/g TOC). The overall kerogen assemblages are type III and subordinate type II, consistent with a gas condensate to a gas volatile oil petroleum system. No marine algal remains are evident in the deepwater sources, nor are any suggested by oil analyses. Oil/condensate chemistries vary widely but the fundamental genetic makeup of these deepwater liquids shares similar characteristics including: (1) high pristane/phytane, oleanane/hopane and bicadinane/hopane ratios, (2) a C29-sterane dominance and the general lack of C30-steranes, (3) high lupanoids, (4) low sulfur and asphaltene, and (5) variable wax content. Gases are mainly thermogenic and the mixing of “biogenic” methane and CO_2 are observed in some shallow Pliocene reservoirs. The generation of oil and gas mostly occurred at “oil window” maturities.

Geochemistry of the eastern Makassar Straits and the area offshore West Sulawesi is generally speculative due to lack of knowledge compared to its western counterpart. However, numerous oil and gas seeps occur in the onshore West Sulawesi area, such as in the Kalosi, Lariang and Karama areas (Figures 9-10).

In the Kalosi area, all of the oils were generated within the oil window (Ro 0.60% to 0.90%) (Coffield et al, 1993). Geochemical analysis of the oils indicate they are paraffinic, low sulfur, moderately low wax to waxy oils with API gravities (where not biodegraded) of 35° to 40°. Except for maturity differences, good correlation exists between the oils and the Eocene in age coals and carbonaceous claystones of the Toraja Formation, based on GC, GC-MS, and carbon isotope data. All of the Eocene coals have high pristane and phytane ratios (6.0-15.20) similar to or greater than the oils. During pyrolysis-GC experiments the coals generated similar waxy hydrocarbon products at maturity. The carbon isotopes for the aromatic fractions are very similar (within 1 per mil) while the tricyclic, tetracyclic and pentacyclic terpane biomarker distributions are the same. The bicadinanes and steranes also both show good correlations. Coals and carbonaceous claystones deposited in fluviodeltaic depositional environments are present in the Kalosi area in the upper portion of the Toraja Formation (middle-late Eocene) and are considered to be the primary source rocks of the oil and gas seeps (Coffield et al. 1993). The rocks contain Type II/III terrestrially influenced kerogens, and have TOC values in the range 31% to 81% and HI values ranging from 158 to 578.

In the Lariang and Karama area there are numerous oil and gas seeps (Bantaya oil seeps, Doda oil and gas seeps in Lariang; Poluhu oil and gas seeps, Lamba gas seeps and Paniki River oil seeps in Karama) (Coffield et al., 1993). Doda, Poluhu and Paniki oils have been characterized geochemically and show terrestrial oil characterization, generated from maturity of 0.8-1.0 % (equivalent vitrinite reflection calculated/Rc from aromatic biomarker of the oil), the Bantaya oil was generated from higher maturity of 1.2 -2.0 % vitrinite reflection calculated. The source rocks are considered to be coals and coaly shales of the Kalumpang/Budung-Budung Formation (Toraja Group, similar with Kalosi area) of middle to late Eocene age.

In offshore West Sulawesi the presence of seeps related to hydrocarbons may have been shown by anomalies found by ALF (airborne-laser fluorescence) (Thompson et al., 1991). Fluors have been identified which are believed to represent hydrocarbon seepage. The largest number of observed fluors occur directly above the South Makassar basin. The coincidence between the area covered by fluors and the basin depocenter is impressive. Most fluors are within the 3.0 second two-way time total sediment isochore. The fluors imply that the South Makassar basin is leaking hydrocarbons on a large scale. This suggests that vertical migration of hydrocarbons from Eocene coals or lacustrine mudstones, is dominant. It is proposed normal faults of rifts provide a pathway through the thick sequence of mudstones for hydrocarbons generated at depth to get to the surface. A few ALF anomalies have been observed in the northern West Sulawesi offshore, immediately offshore of the Lariang-Karama basins. Several seeps have been logged onshore as discussed above, considered to be sourced from Eocene coals. It is likely that the offshore fluors have a similar origin. The ALF results are encouraging for the hydrocarbon potential of the South Makassar basin, and provide some encouragement for North Makassar basins.

Recent regional “sea-seep” identification in Indonesia was conducted by several companies under the direction of the Directorate General of Oil and Gas (Migas) using another technology (Noble et al., 2009). The program was called “Sea Seep” piston coring program, taking cores of the sea bed at locations which indicated anomalously seep-related morphology based on multibeam data. The samples then were analyzed geochemically including: head-space gas analysis, stable carbon-12/13 isotope ratios of each C1-C5 component and carbon dioxide, total scanning fluorescence (TSF) from bagged sediment sections and gas chromatography for the whole C15+ solvent extract. From these analyses, screening criteria were applied to identify migrated liquid petroleum and gaseous hydrocarbons in order distinguish them from background readings. C1-C5 gas composition and carbon isotopic ratios were also used to distinguish biogenic from thermogenic hydrocarbons. The presence of crude oil was detected based on signatures from TSF and C15+ whole extract gas chromatography. The area of West Sulawesi offshore was surveyed in this program. An oil seep from this area is quite different from the typical non-marine oils of the Mahakam Delta. The seep clearly exhibits marine carbonate/marly source characteristics, with no strong evidence of Tertiary plant biomarkers (Figure 11). There is presently insufficient seismic/geologic information to clearly define the source rock age, and the biomarker data were not sufficiently diagnostic to distinguish between a Tertiary and Mesozoic source. Nevertheless, the oil seep appears to represent a new petroleum system in this region. The seep information should be integrated with seismic interpretation of basin structure, stratigraphy, and potential migration conduits, resulting in an assessment of the most probable underlying petroleum system.

Based on geochemical characterization of macroseeps which occur in the onshore areas of West Sulawesi, and microseeps detected indirectly based on ALF and the SeaSeep program of sea bed cores in the West Sulawesi offshore areas, it looks as if terrestrial middle-late Eocene coals and coaly shales are the main source rocks in this region. Subordinate to this is possibly marine marls or carbonates younger in age. Eocene source rocks were deposited within rifted grabens formed when Western Sulawesi rifted from Eastern Kalimantan. Shallow water carbonates dominate the rift shoulders and deepwater mudstones dominate the centre of this sediment-starved rift. The only widespread development of coarse clastics, of Early to Middle Eocene age, is at the base of the Tertiary sequence resting directly on the pre-Tertiary. Coals are well developed in the Middle Eocene.

Lacustrine shales may occur in the depocenters away from areas of coarse sediment input. Coals and lacustrine source rocks of variable quality have been identified in wells and outcrops surrounding the Makassar Straits. Clear syn-rift geometries are visible on seismic.

Geochemical Risks Based on Recent Well Results

Until the end of April 2012, twelve wells have been drilled in six Blocks of the deep-water area of West Sulawesi offshore, in the North Makassar and South Makassar Basins (Figure 12). The first well in the region, Rangkong-1, was drilled by Exxon Surumana in 2009. The well failed to find hydrocarbons. Exxon moved to their other block in this area, Mandar Block, and drilled three wells; all the block's firm well commitments, called Sultan-1 (2009), Kris-1 (2010), Kris-1 ST (2010). Sultan-1 discovered uneconomic gas possibly biogenic in nature. Kris-1 and Kris-1 ST were dry holes due to tight reservoir and absence of reservoir, respectively (Bacheller III et al., 2011). Marathon drilled their first well in the Pasangkayu Block; Bravo-1 (2010) and continued with Romeo-1 (2010, mechanical trouble), Romeo-B1 (2010, mechanical trouble), and Romeo-C1. Bravo-1 and Romeo-C1 failed to find hydrocarbons despite good carbonate reservoir objectives being encountered (Armandita et al., 2011). The turn then came to ConocoPhillips in Kuma Block, they drilled the Kaluku-1 well (2011). Prospectivity of West Sulawesi offshore in South Makassar Basin was tested by the Lempuk-1 well, drilled by Talisman in Sageri Block in late 2011. The last two wells in the area have been drilled by Statoil in the Karama Block, targeting Neogene objectives in thin-skinned structures, the wells are Gatotkaca-1 (2012) and Anoman-1 (2012).

Most of the wells drilled were dry, and after being evaluated by their operators the main reason for failure was thought to be due to imperfect seal. However, we think that the reason for the dry or uneconomic wells in the region is mostly due to geochemical risks (very limited or no source in low areas prognosed as the kitchen, immaturity, recent generation/too late generation, migration barriers and minimal volumes).

The altered volcanics encountered in the Rangkong-1 well (Exxon Surumana, 2009), instead of the carbonate objective, are fractured. This lithology could could be a reservoir in the same was as the fractured volcanics of the Jatibarang oil field in onshore West Java. No hydrocarbon shows could indicate failure of the low areas flanking the Rangkong structure to the west and east of the structure to generate hydrocarbons. No source rocks deposited or lack of maturity could be an explanation for the dry Rangkong-1. Lack of maturity or too late generation is also confirmed by data fluid inclusion volatiles (FIV) analysis performed in the volcanics. FIV data demonstrate the presence of an active thermogenic hydrocarbon system with migrated wet gas and oil inclusions, but that were probably formed at about present day burial conditions (Bacheller III et al., 2011). This reveals that the generation of petroleum is Recent, implying that the volumetrics will be minimal. The top of the pinnacle reef of Sultan-1 (Exxon Mandar, 2009) contains a 102 m column of 97% methane gas. Isotopic evidence for the origin of the gas is inconclusive at present with possible mixing between thermogenic and biogenic sources but the presence of biogenic gas may indicate a lack of maturity.

The Bravo-1 (Marathon Pasangkayu, 2010) and Romeo-C1 (Marathon Pasangkayu, 2011) wells encountered thick and good carbonate reservoirs, 20-25 % in porosity. Pressures and fluid samples confirm the primary objectives are wet (Armandita et al., 2011). Preliminary analysis indicates charge is the most likely failure mechanism, however, source presence and migration pathway issues cannot be ruled out. We consider that limited or no source potential rocks were deposited within the low area to the west of Romeo prognosed as the kitchen. Whereas, the prognosed kitchen of Bravo may suffer from a lack of maturity due to too thin burial sediments and inversion.

Implied Post-Drilling Evaluation on Source, Maturity and Migration

Pre-drill the petroleum system/play was described as Early to Middle Eocene syn-rift coals and lacustrine shales as source rocks for Oligocene to Miocene carbonate buildups on footwall highs, sealed by deep water marine Miocene to Pliocene shales (Figure 13). Thick Pliocene to Recent sedimentation drove hydrocarbon maturation (Bacheller III et al., 2011). Post-drill the petroleum system shows some modifications to the pre-drill play summary.

The source systems of Eastern Kalimantan, Makassar Straits and Western Kalimantan that are proven and potential are summarized in Figure 14. Basically, there are two groups: West Sulawesi and Mahakam source systems.

Rifted grabens or low areas formed when Western Sulawesi separated from Eastern Kalimantan are not always kitchens (generating source pods). Not every low area mapped in each block is a kitchen. Which is a kitchen and which is not a kitchen is not easy to determine but it can be approached using the internal seismic character of the low areas which usually show weak seismic amplitude indicating a low-energy environment good for source preservation. Paleogeographic analysis should be constructed for low areas in the blocks in order to know their depositional environments. Source preservation is best in low energy anoxic environments such as fresh water lakes, lagoons, deltaic and coastal swamps, restricted circulation basins, outer shelf deposition areas under the minimum oxygen layer, and silled deep ocean basins.

The absence of or very limited sources deposited in the graben areas surrounding Rangkong and Romeo structures in the Surumana and Pasangkayu areas, respectively may relate to the rate of rifting of the North Makassar Strait in this area which could be too rapid. Significant extension usually results in rapid subsidence potentially resulting in an absence of coaly or lacustrine, synrift source rocks. Hence the entire syn-rift section could be marine or sufficiently diluted to not be effective. It was also recognized that a number of wells around the margins of the Makassar Straits encountered only deep-water Eocene sediments. In terms of rate of rifting, South Makassar Basin opening was slower than its northern counterpart, providing better source quality in the South Makassar Basin due to lack of organic richness dilution.

Oil geochemistry of seeps onshore show that prognosed Eocene (early-late) sources deposited in early-main rifted grabens in terrestrial-transitional environments (can be lacustrine, deltaic, coastal swamps) are the main source facies for the West Sulawesi offshore region. Subordinate sources are marine sources of the postrift or sagging phases, but this is not yet proven regionally.

Maturity may be a significant problem in the West Sulawesi offshore area. The FIV data of Rangkong indicating recent generation of fluid inclusions within its volcanic deposits and the biogenic/thermogenic gas of Sultan may indicate early maturity of source rocks. It appears that maturity of Paleogene source rocks of this region depends very much on depth of burial and the tectonic loading of the overlying thin-skinned deformation. The burial sediments in the North Makassar Basin are getting thinner westward from the Sulawesi coastal line. This causes blocks located in the middle of the basin to be later in petroleum generation compared to blocks located near the Sulawesi coastal line which have thicker burial sediments. Thin-skinned deformation of the West Sulawesi offshore has taken place from the Mio-Pliocene until now as revealed by the uplifted seabed due to Recent deformation. Since this deformation has become the tectonic loading mechanism for maturity of Paleogene sources, the maturity is also a late occurrence issue following the timing of thin-skinned deformation.

The Neogene play of West Sulawesi Offshore is more challenging from a petroleum geochemistry point of view. The challenges are related to: (1) presence of regional and very thick shale decollement/detachment below the thin-skinned structures that may act as a barrier to migration from Paleogene sources to Neogene reservoirs, (2) lack of organic-rich source rocks in the Neogene section due to the volcanic-clastic nature of the sedimentary sections and (3) lack of maturity due to thin burial sediments and recent deformation.

The Neogene thin-skinned structures of the West Sulawesi Offshore foldbelts have their own problems of source, maturity and migration (Figure 15). The structures are underlain by decollement/detachment surfaces made up of shale sections which are usually thick and overpressured making a perfect seal or roof to migration blocking upward movement from Paleogene sources to Neogene reservoirs. Therefore, the Neogene play should have its own source(s) and form a closed system. This is not a problem at all for the Neogene sections of western Makassar Strait where the voluminous Mahakam delta sediments are rich in coals and carbonaceous shales. Debris of coals and coaly materials were deposited downdip from the faulted anticlines of the thin-skinned/toe-thrust structures of the Mahakam deep-water area. These matured due to the very thick deltaic burial sediments, and the generated petroleum migrated updip and became trapped in the faulted anticlines of the toe-thrusts or in stratigraphic traps like updip pinchouts of sands.

The situation is much different for the Neogene section of West Sulawesi Offshore. The Neogene sediments were sourced mainly by the Neogene volcanic arcs of Western Sulawesi (Camba/Enrekang volcanics) which are poor in organic content. Neogene deltas were not well developed in West Sulawesi and the Neogene sections may be generally lean in organic content.

Local enrichment to provide carbonaceous shales in Neogene sections is possible and may occur in more marine environments due to deposition in the post-rift or sagging phase. However, maturity may be then also be a problem due to the young and thin burial sediments. Toward onshore Western Sulawesi, offshore thin-skinned structures changed in structural style to become thick-skinned structures. Faults connect the Paleogene to Neogene sections and become migration conduits as proved by oil seeps in Neogene section that are geochemically characterized and show Eocene sources.
A summary of the petroleum system elements and processes for the West Sulawesi offshore areas is shown in Figure 16, incorporating the Makassar Straits opening and thin-skinned deformation events. Development of a working petroleum system depends upon these events.

CONCLUSIONS

A number of new issues have been raised following the results of the drilling in the West Sulawesi offshore area which are listed below.

1. Paleogene carbonate and clastic reservoir objectives in the Makassar Straits are not randomly distributed, they were controlled by the Paleogene paleogeography.

2. Eocene deltas of Western Sulawesi could be better than those of Eastern Kalimantan.

3. Miocene-Pliocene deltas of Eastern Kalimantan are prolific for sources and reservoirs, but their counterparts in Western Sulawesi are poor. There is no evidence that Mio-Plio deltaic sediments from Eastern Kalimantan continued into the West Sulawesi offshore.

4. Volcanics were dominant in Western Sulawesi onshore during the Miocene-Pliocene, and could be the main sources for its offshore sediments which are now involved in thin-skinned deformation. As a result the negative aspects of the sediments being immature and volcanic diagenetic changes should be considered when considering them as reservoir targets.

5. The rate of rifting/opening between North and South Makassar is different. North Makassar opened at a faster rate than South Makassar and as a result the issue of organic dilution due to too rapid sedimentation in North Makassar should be considered.

6. Due to the presence of decollements/basal detachments underlying the thrust structures in the deepwater Makassar Straits and the thin-skinned fold thrust belts in west Sulawesi offshore, generation-migration-entrapment of petroleum should be targeted within a closed-system, sourced internally, with associated migration.

7. The Miocene-Pliocene toe thrusts of the deepwater western Makassar Strait are loaded with debris from coaly sources, eroded from marginal marine deltas during lowstands, and deposited within the synclinal toe-thrust area. The Mio-Pliocene-Recent thin-skinned fold-thrust belts of West Sulawesi offshore may not have enough source material present and be of sufficient quality due to their volcanic provenance.

8. The Neogene-Quaternary multiple thrust sheets of thin-skinned deformation overlying the Paleogene system in West Sulawesi offshore have played a role as a tectonic overburden maturing the underlying Paleogene sources. But the thin-skinned deformation has taken place during Pliocene-Recent times, meaning that HC generation-migration-entrapment in this area has also been very recent.

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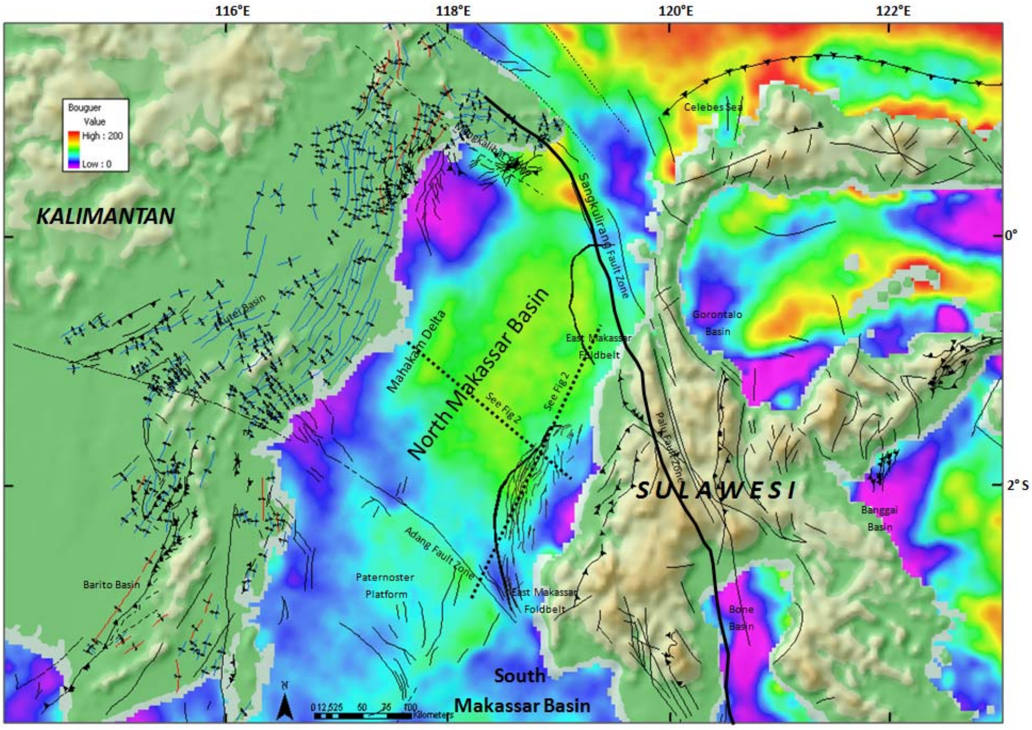


Figure 1 - Major Structural Elements of Trans-Eastern Sundaland, including Eastern Kalimantan, the Makassar Straits and Western Sulawesi.

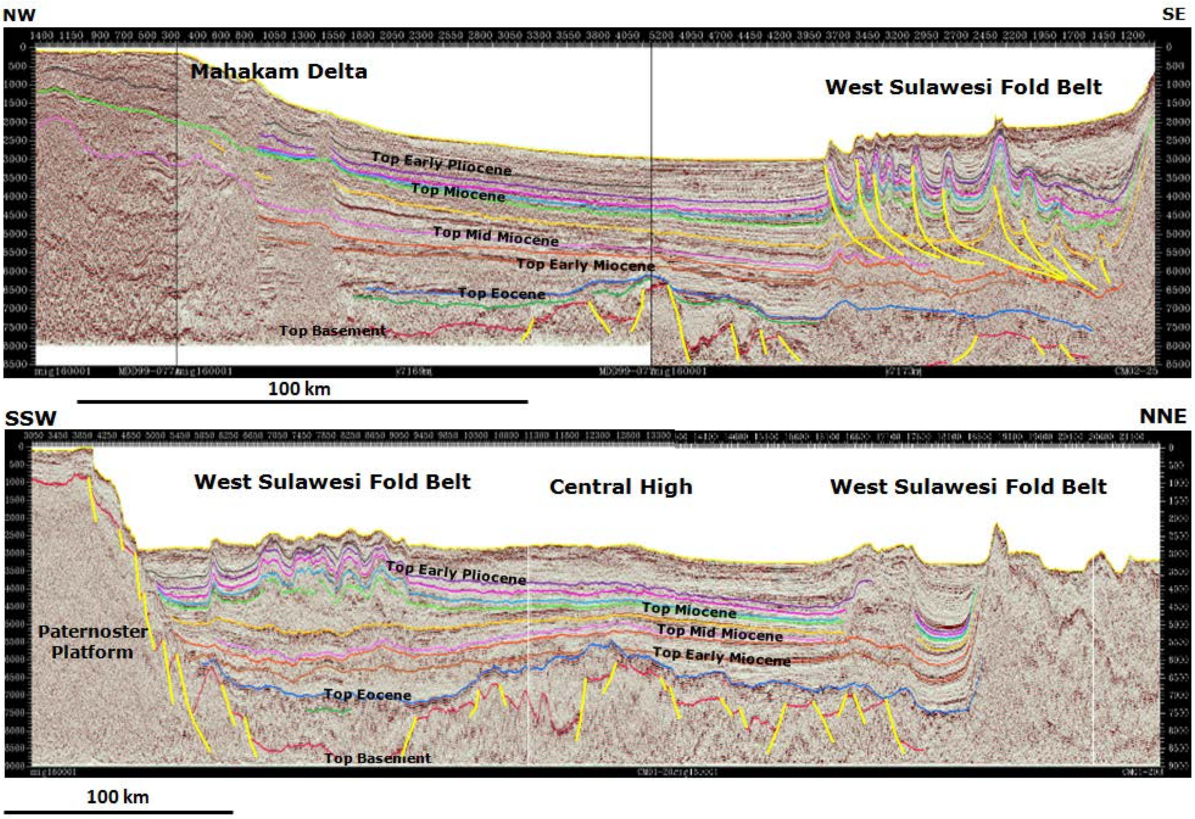


Figure 2 - Seismic sections across Trans-Eastern Sundaland, showing Paleogene rifting and Neogene compression. Locations of the seismic lines see Figure 1.

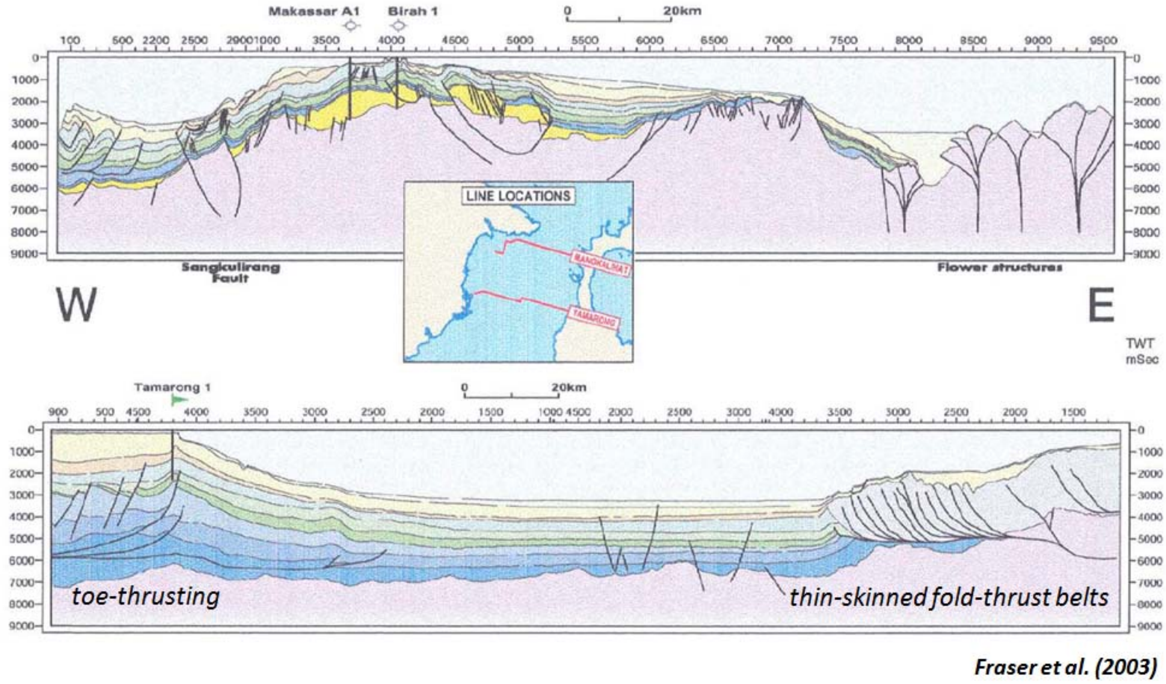


Figure 3 - Structural Styles of Trans-Eastern Sundaland (Fraser et al., 2003).

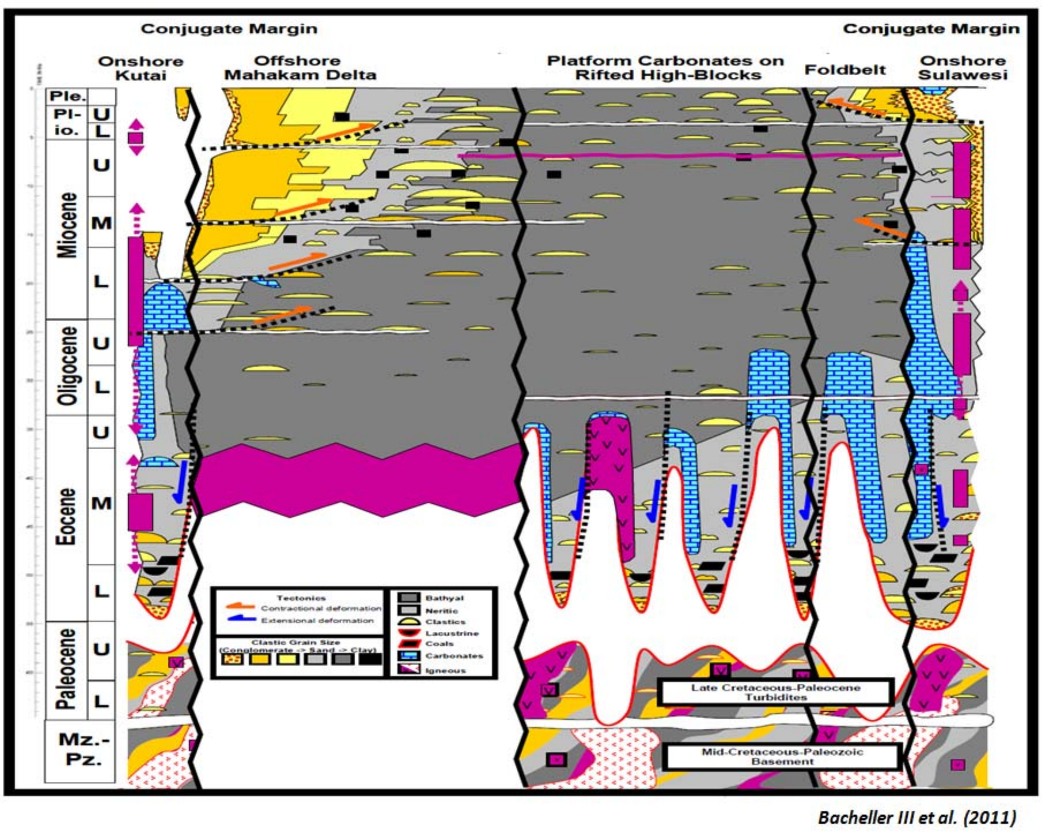


Figure 4 - Tectono-stratigraphy of the Makassar Straits both at its western and eastern sides, different sedimentary packages will affect its petroleum geology (Bacheller III et al., 2011).

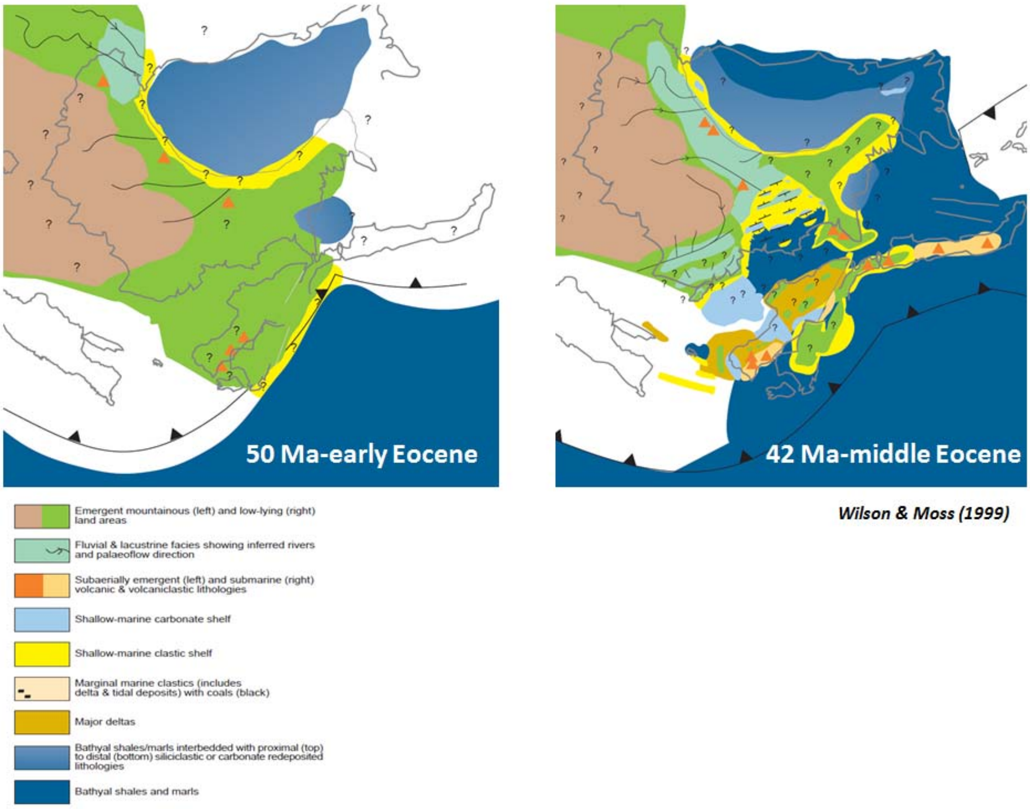


Figure 5 - Paleogeography of Kalimantan and Sulawesi during early-middle Eocene, affected development of Paleogene sources, reservoirs and seals (Wilson and Moss, 1999).

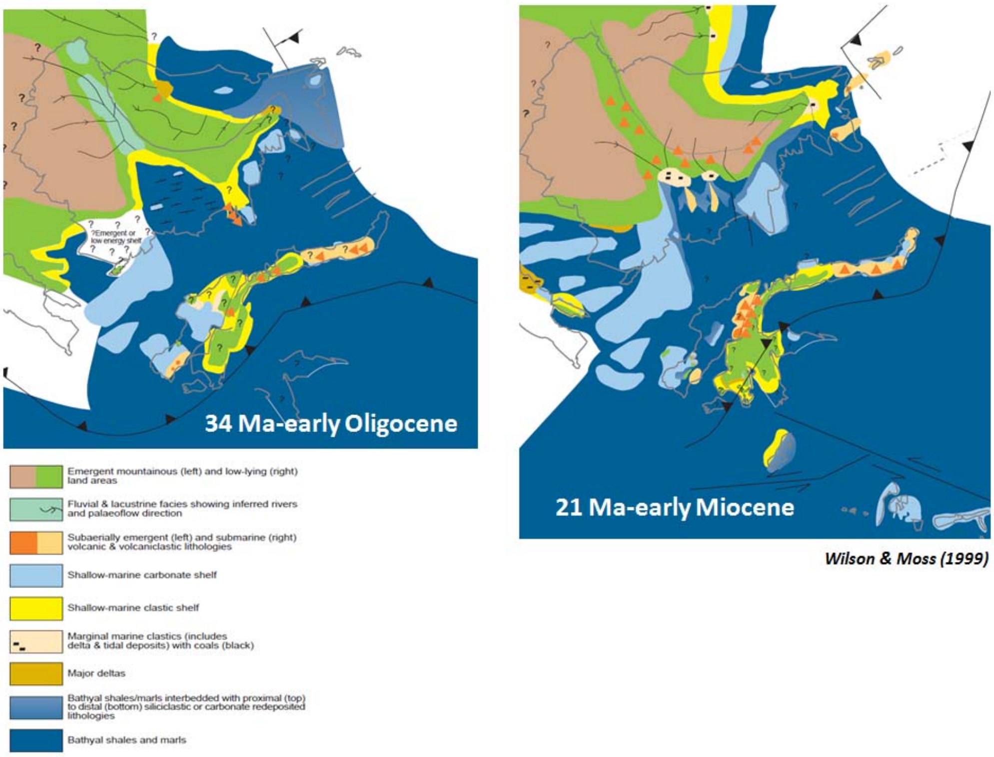


Figure 6 - Paleogeography of Kalimantan and Sulawesi during early Oligocene-early Miocene, affected development of Paleogene sources, reservoirs and seals (Wilson and Moss, 1999).

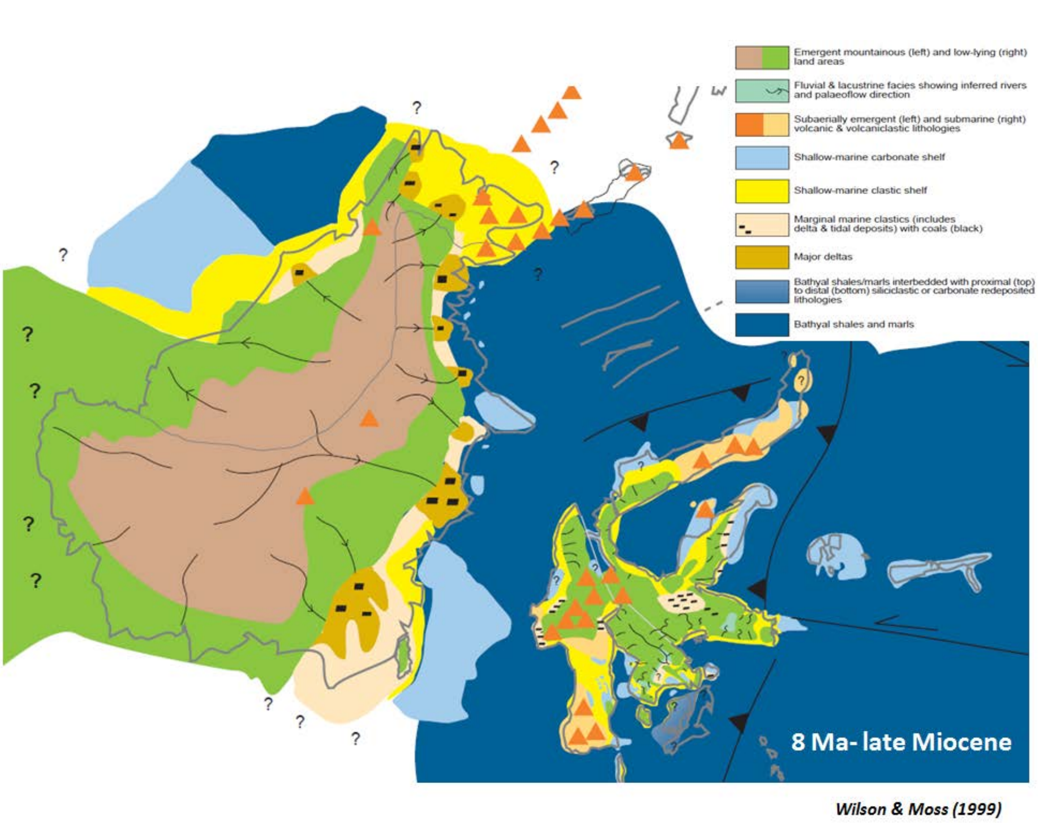


Figure 7 - Paleogeography of Kalimantan and Sulawesi during late Miocene, affected development of Neogene sources, reservoirs and seals (Wilson and Moss, 1999).

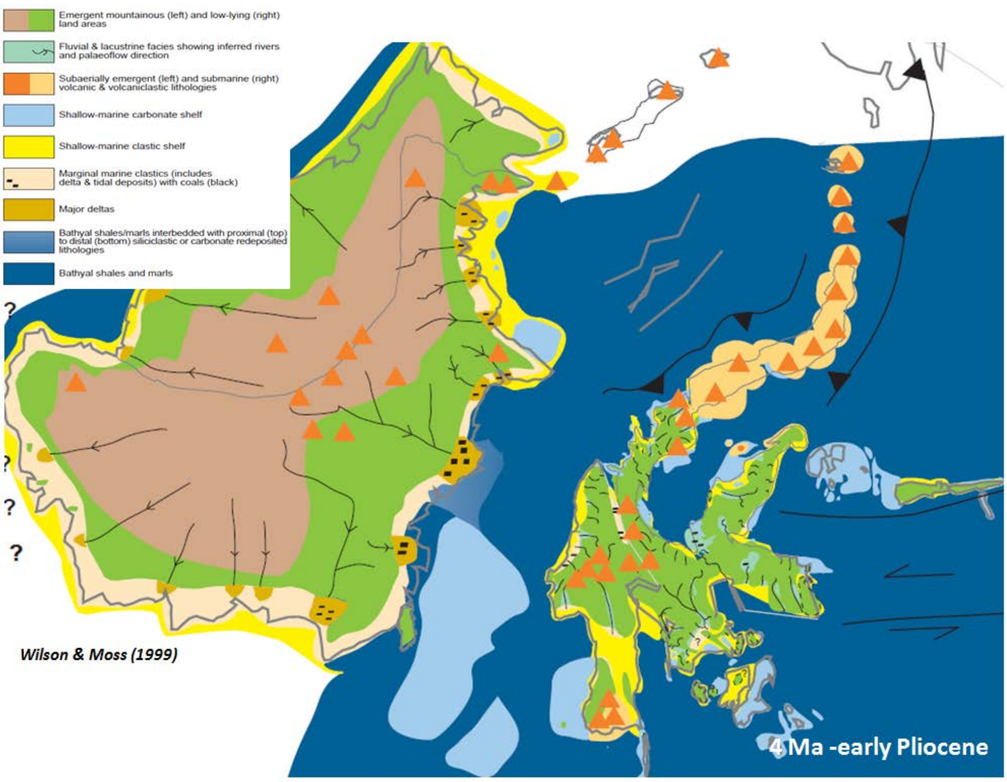


Figure 8 - Paleogeography of Kalimantan and Sulawesi during early Pliocene, affected development of Neogene sources, reservoirs and seals (Wilson and Moss, 1999).

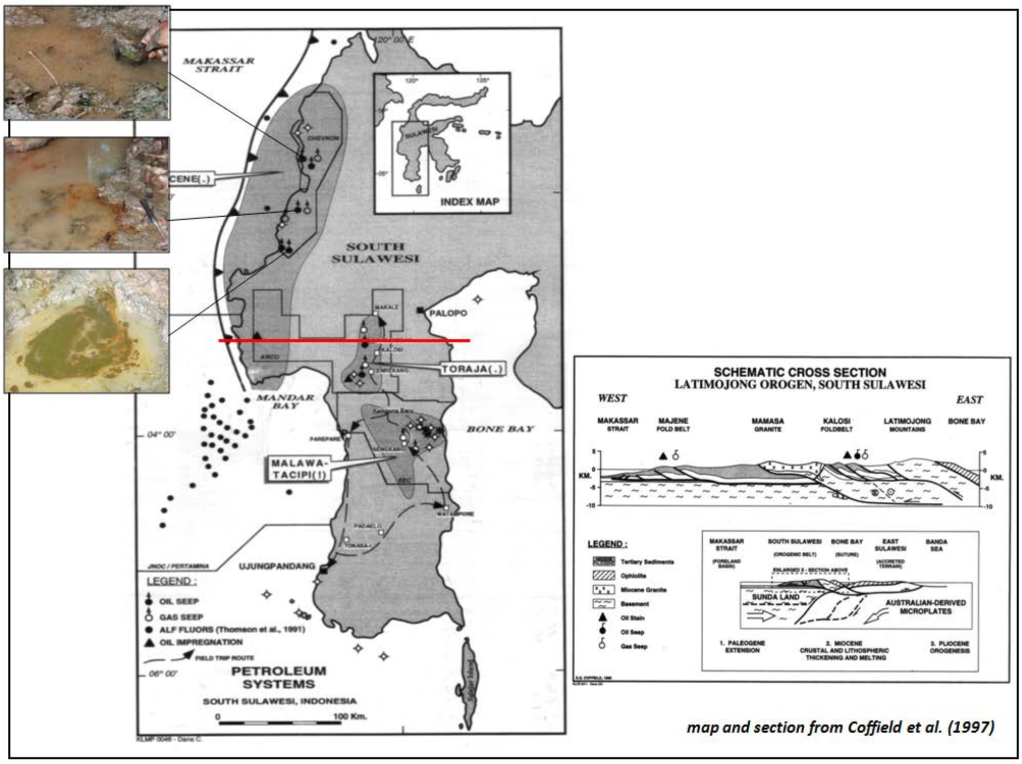


Figure 9 - Onshore and offshore oil and gas seeps of West Sulawesi. Onshore seeps are macroseeps, offshore seeps are microseeps based on ALF (airborne laser fluorescence) survey reported by Thompson et al. (1991).

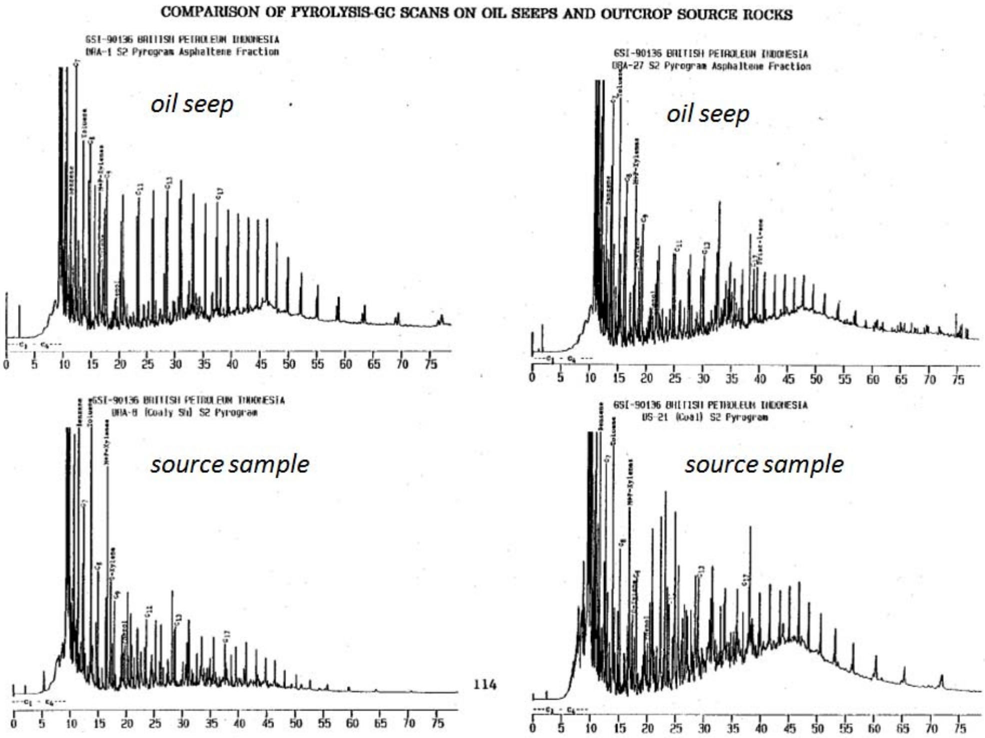


Figure 10 - Comparison of pyrolysis gas chromatograph (GC) scan of oil seeps and source samples of coaly material of Eocene Toraja Formation, West Sulawesi, showing good correlation.

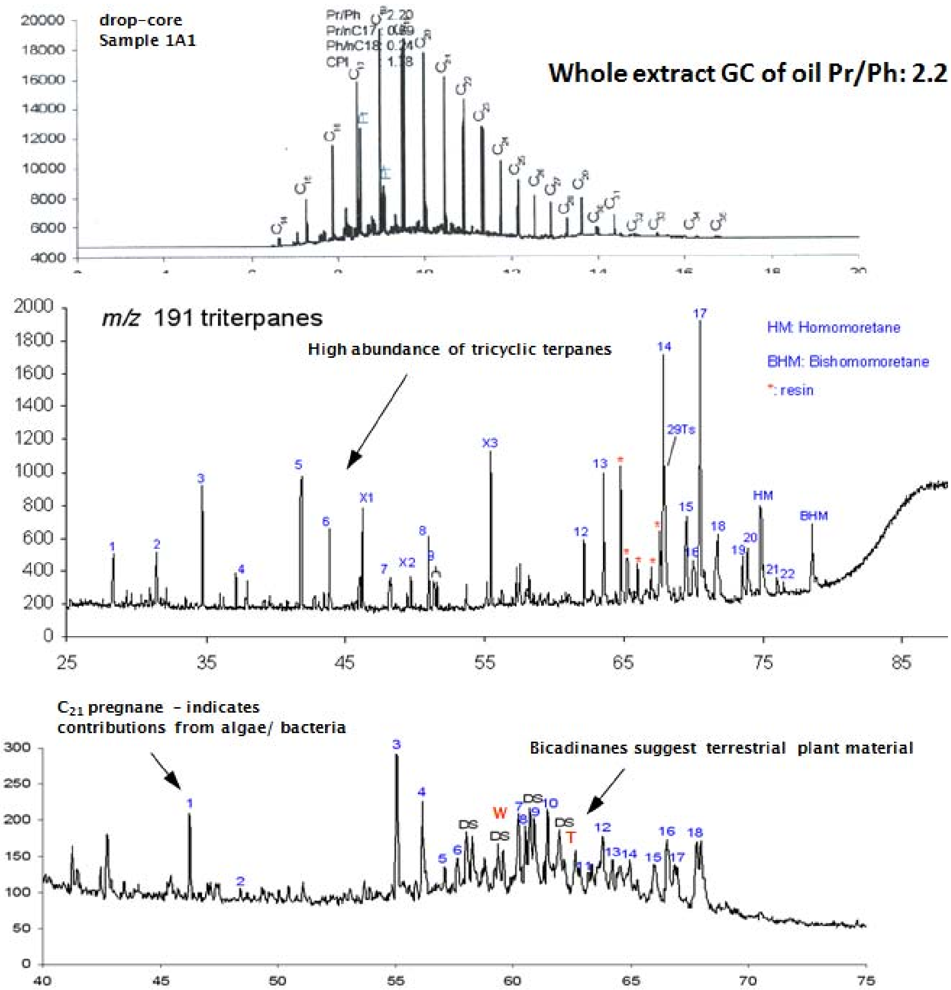


Figure 11 - Biomarkers of microseep from sea bed core of West Sulawesi offshore, showing a marine environment. They do not correlate with terrestrial-source oil seeps in onshore Sulawesi, providing new opportunity.

- ExxonMobil Surumana
  1. Rangkong-1 (2009)
- ExxonMobil Mandar
  2. Sultan-1 (2009)
  3. Kris-1 (2010)
  4. Kris-1 ST (2010)
- Marathon Pasangkayu
  5. Bravo-1 (2010)
  6. Romeo-1 (2010)
  7. Romeo-B1 (2010)
  8. Romeo-C1 (2011)
- COPI Kuma
  9. Kaluku-1 (2011)
- Talisman Sageri
  10. Lempuk – 1 (2011)
- Statoil Karama
  11. Gatotkaca – 1 (2012)
  12. Anoman – 1 (2012)

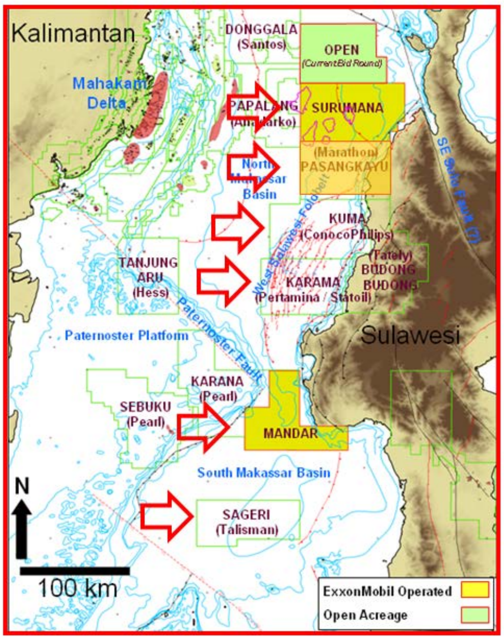
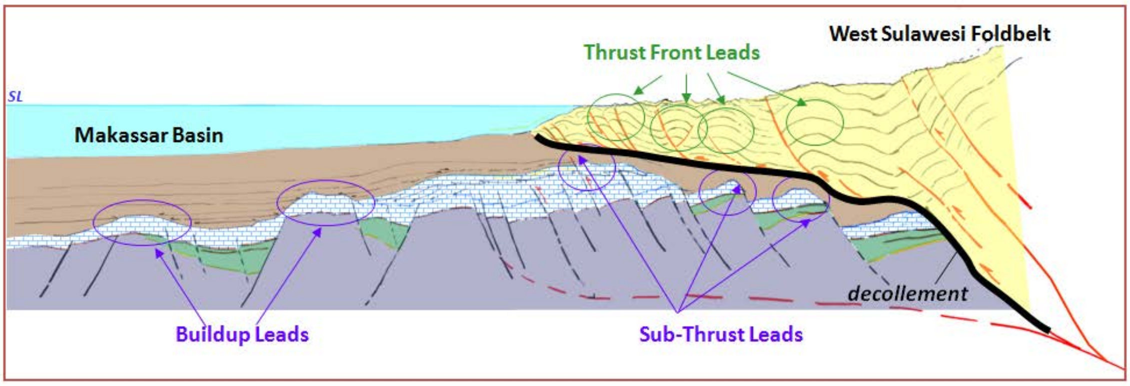


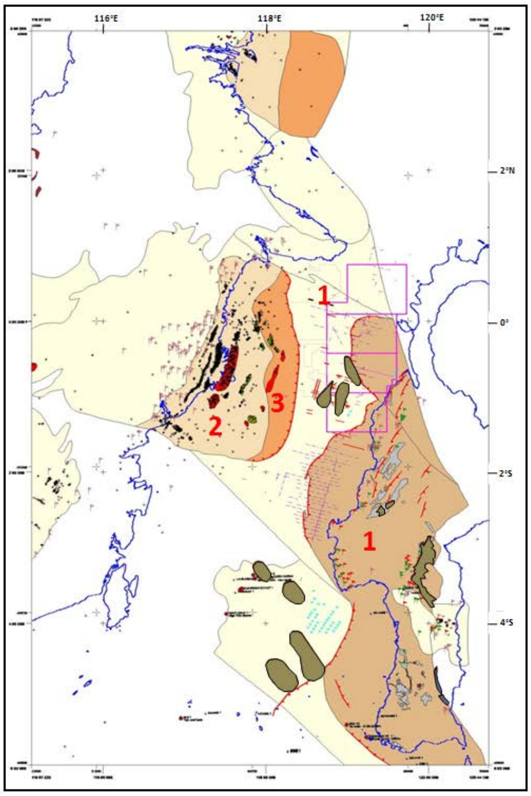
Figure 12 - Wells drilled in deep-water area of West Sulawesi offshore to date (end of April 2012).



- **Lead types**
  - Carbonate Buildups in deepwater
  - Carbonate Buildups or Structural Closure sub-thrust
  - Syn-rift clastics
  - Shallow structures within thrust front, clastic reservoirs

- **Two greater source areas & pattern of migration**
  - Closed Neogene system in thin-skinned fold & thrust belts
  - Closed Paleogene system in subthrust areas below decollement
  - Paleogene-Neogene systems in thick-skinned fold & thrust belts

Figure 13 - Schematic plays of West Sulawesi Offshore. Paleogene plays look to be separated from the Neogene plays by decollement/detachment surface. Sources, reservoirs and seals of the Paleogene plays related to syn-rift, postrift and sagging phases. Sources, reservoirs and seals of the Neogene plays related to syn-orogenic deformation phases of thin-skinned structures.



West Sulawesi Source System
Source - Syn-Rift Facies (Eocene): Non-marine (1), partly marine in Neogene offshore.
Seen in onshore outcrops and on seismic (Eocene graben)
Onshore seeps on Sulawesi
Eq. with Tanjung/Barito.

Mahakam Source System
Source - Deltaic Facies (Miocene): Coals (2)
Source - Transported Terrestrial (Miocene-Recent): (3)

Eocene graben (not all mapped)

Figure 14 - Source Systems of Trans-Eastern Sundaland, including Eastern Kalimantan, the Makassar Straits and Western Sulawesi. Outline of source pods/grabens are indicated (for examples only, not all grabens are mapped/shown).

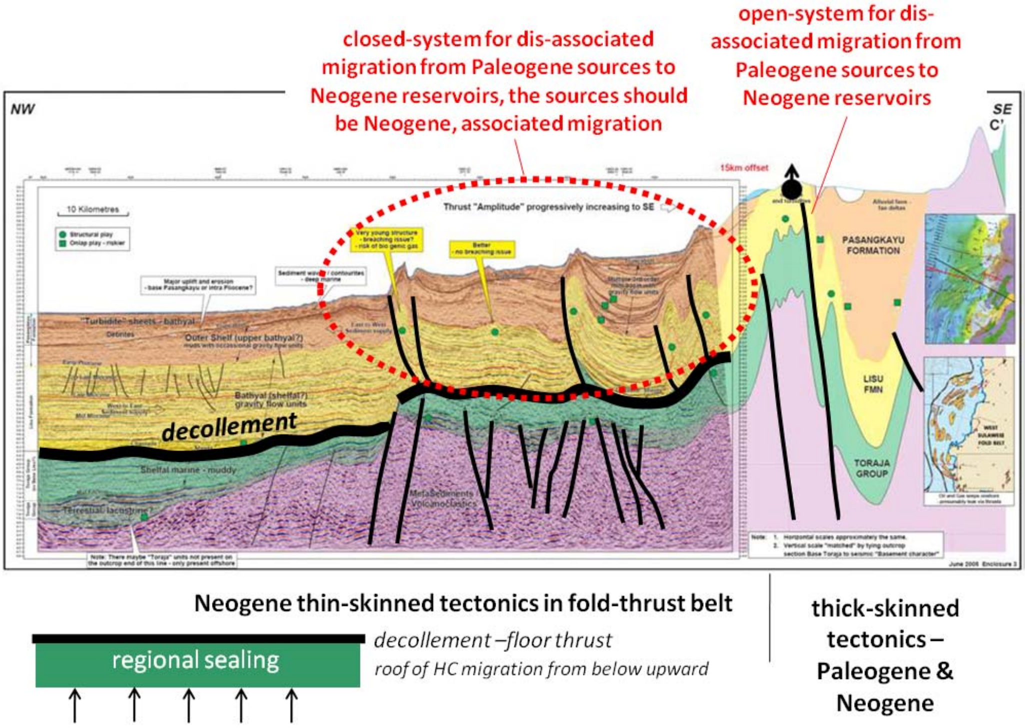


Figure 15 - Implications on the presences of thin-skinned and thick-skinned tectonics in West Sulawesi offshore and onshore areas. Decollement surface underlying thin-skinned structures will block upward migration from Paleogene sources to enter Neogene reservoirs, hence Neogene plays should have their own sources (closed system, associated migration/charging). Whereas, in thick-skinned structures, deep-seated faults can bring generated petroleum from Paleogene sources to Neogene reservoirs (open system, disassociated migration/charging).

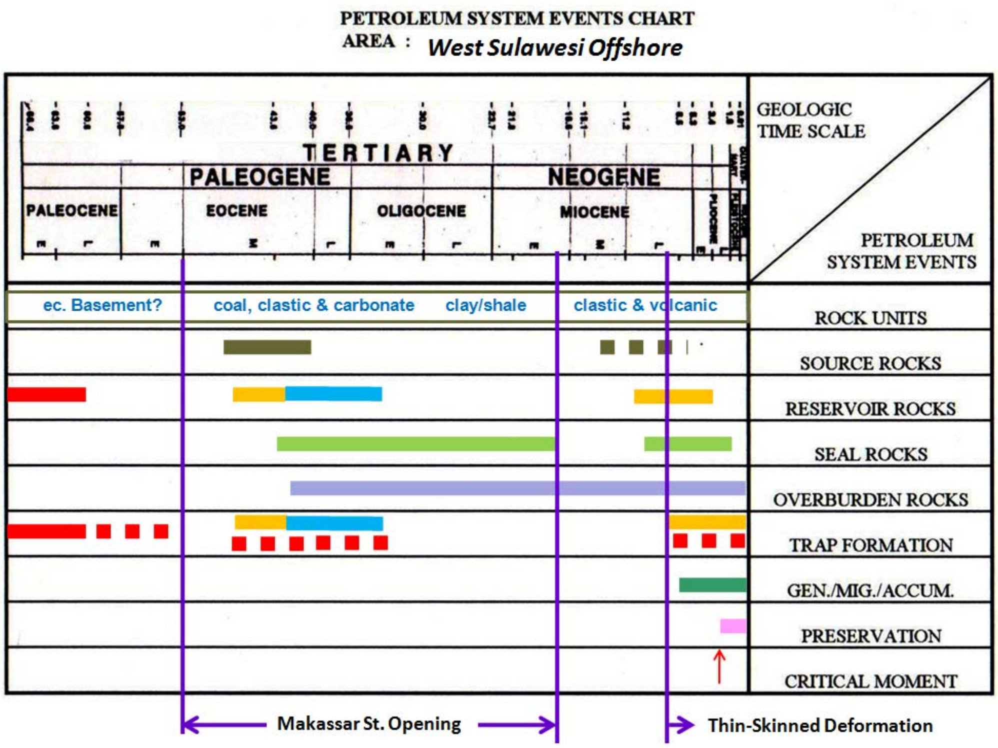


Figure 16 - Petroleum system events chart of West Sulawesi Offshore areas (proven and potential), incorporating events of Makassar Straits opening and thin-skinned deformation of West Sulawesi foldbelts.