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RIFTING HISTORY OF THE MAKASSAR STRAITS: NEW CONSTRAINTS FROM WELLS PENETRATING THE BASEMENT AND OILS DISCOVERED IN EOCENE SECTION - IMPLICATIONS FOR FURTHER EXPLORATION OF WEST SULAWESI OFFSHORE

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ABSTRACT

The opening mechanism and nature of the basement underlying the North Makassar Straits has been debated for almost thirty years. Two leading opening mechanisms are: tectonic escape through major strike-slip extension and back-arc rifting due to subduction rollback. The basement has been debated as continental or oceanic.

This study presents hard data of the North Makassar Straits' basement penetrated by two exploration wells: Rangkong-1 (ExxonMobil Surumana, 2009) and Kaluku-1 (ConocoPhillips Kuma, 2011). The basement's analyses include: petrography, X-ray diffraction, biostratigraphy, petrochemistry, magnetic susceptibility, multi-isotope geochronology, and organic geochemistry. Oils discovered by Kaluku-1 well in Eocene section provides further information based on analyses of bulk properties, carbon isotope, and various biomarkers. These hard data, never published anywhere before, are the basis for this study.

The new data constraint that the basement of the Makassar Straits is Gondwanan Paternoster-West Sulawesi microcontinent, thinned due to rifting from the Early/Middle Eocene to Early Miocene time as response to back-arc rifting related to subduction roll back in SE Sundaland. The Eocene rifted grabens and horsts were the sites for shallow lacustrine sources, sandstone reservoirs, and traps.

Kaluku oil discovery show the active petroleum system in West Sulawesi Offshore. Based on Kaluku discovery, further exploration should target the area to the east of Kaluku until transition zone with Onshore Sulawesi. Here the source rocks are considered to be thicker, better quality, earlier maturation hence generating more oils. The sandstone reservoirs will also be thicker. Syn-rift play may also be significant here, but existing seismic data preclude the evaluation. New 2D high resolution or 3D seismic data are required for better evaluation.

Dry wells drilled here by various operators from 2009-2012 did not condemn the area since none of these wells targeted the Eocene section on rifted structures that actually should be.

INTRODUCTION

The Makassar Straits located between Kalimantan and Sulawesi Islands in Central Indonesia are a north-south orientated seaway, around 700 km long, 125-400 km wide with maximum water depths almost 2500 m. Bathymetrically, the Makassar Straits are subdivided into the northern and southern depressions and are hence sometimes referred to as the North and South Makassar Basins (Figure 1).

While the Paleogene history for the opening of the Makassar Straits is commonly agreed by many authors, the mechanism of the opening of the Straits and nature of the basement underlying the straits have been the subjects of considerable scientific debates. The debates in history are mainly because of lack of data representing direct data on the geology of the Makassar Straits. Most debates were based on modeling of subsidence history, gravity, magnetic and plate tectonics.

From 2007-2012 deepwater area of the Makassar Straits were intensively explored. Speculative seismic surveys were acquired, working blocks were awarded to oil companies. They did exploration studies, acquired detailed 2D-3D seismic data and other geophysical-geological data. Teens of exploration wells were drilled. Satyana et al. (2012) summarized these activities, reported the exploration results and its implications to geological knowledge of the Makassar Straits.

This paper will present current data on basement of the Makassar Straits penetrated by recent wells that

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directly show the nature of the basement underlying the Straits. One well encountered oils from Eocene section of the Makassar Straits will also reveal direct data on the mechanism of the opening of the Straits. Based on these recent data, the opening history of the Makassar Straits and its implications on petroleum geology of the area will be discussed.

Early exploration in deepwater area of the Makassar Straits at West Sulawesi Offshore was disappointing due to numerous dry holes. However, one of the wells encountered oil on the objective which were not considered on the prognosis. Early dry holes will reduce risks of later wells, and the occurrences of oils in new objective should positively take into account to continue exploration in this area. The paper will address this matter.

DATA AND METHODS

This study mainly presents hard data of the North Makassar Straits' basement penetrated by two exploration wells: Rangkong-1 (ExxonMobil Surumana, 2009) and Kaluku-1 (ConocoPhillips Kuma, 2011) – Figure 1, unpublished so far. The data are the results of laboratory analyses, including petrography, X-ray diffraction, biostratigraphy, petrochemistry, magnetic susceptibility, multi-isotope geochronology, organic geochemistry of rocks, and reservoir analysis; as well as bulk properties, carbon isotope, and various biomarkers of oils.

The published literatures and unpublished data are examined to analyze to know the nature of the basement underlying the Makassar Straits, synthesized with seismic lines to discuss the rifting history of the Makassar Straits, and its implications on petroleum geology of the area, especially West Sulawesi Offshore to see the possibility for further exploration.

RESULTS

Models of Formation, Age, and Nature of Basement

East Kalimantan and West Sulawesi were part of a single area in the Late Mesozoic (e.g. Katili 1978; Hamilton 1979) but were separated during the Cenozoic by the opening of the Makassar Straits. There has been debate about the age of formation of the straits (e.g. early accounts of Katili 1978; Hamilton 1979 favored Miocene separation of Sulawesi and Kalimantan) but an Paleogene age is now generally accepted.

The mechanism of opening has also been the subject of controversy and its cause remains uncertain. Most authors have favored an extensional origin for the straits (Katili 1978; Hamilton 1979; Situmorang 1982, Wissmann 1984; Cloke 1997; Guntoro 1999), with the Middle Eocene as the beginning of rifting (Situmorang 1982a, b; Hall 1996; Moss et al. 1997; Guntoro 1999; Moss & Chambers 1999; Calvert & Hall 2003, 2007) but no agreement about basement type.

Hamilton (1979) showed an oceanic spreading center down the entire length of the straits and interpreted several NW–SE transform faults. Hall (1996) proposed that oceanic spreading in the Sulawesi Sea during the Middle Eocene propagated towards the southwest into the northern straits. Fraser & Ichram (2000) interpreted there to be oceanic crust beneath the northern straits and southern straits as far south as latitude 6°S. The Makassar Straits have also been interpreted as a remnant oceanic basin (Malecek et al. 1993), a back-arc basin (Parkinson 1998), and Guntoro (1999) suggested that extension was due to trench rollback and sinking of a plate subducting east of a magmatic arc beneath West Sulawesi. Others have argued that rifting never reached the stage of oceanic spreading (e.g. Burollet & Salle 1981; Situmorang 1982a, b). The inversion on the west side of the straits in East Kalimantan (Moss et al. 1997; Moss & Chambers 1999) from the Early Miocene, and eastward propagation of folding and thrusting, have suggested to some that the straits have a flexural origin. On the east side there was development of a fold-and-thrust belt in Western Sulawesi during the Miocene (Coffield et al. 1993; Bergman et al. 1996; Guritno et al. 1996) or later (Calvert 2000a, b; Calvert & Hall 2003, 2007) and, thus, the straits have been interpreted as a foreland basin formed after Early Miocene continent–continent collision in Sulawesi (Coffield et al. 1993; Bergman et al. 1996) in response to thrust loading on one or both sides.

The South Makassar Straits are almost certainly underlain by continental crust. They are relatively narrow and water depths are mainly less than 2 km. There are shelves with thin sedimentary cover above basement to the east and west. Granite and pre-Cenozoic metamorphic rocks are known from boreholes that reach the basement. Although Hamilton (1979) interpreted an oceanic spreading center, apparently based on the shape and morphology of the basin, as did Fraser & Ichram (2000), back-stripping and gravity modeling by Situmorang (1982a, b) indicate continental crust is much more likely, and this is now generally accepted. Recent seismic lines show up to 7 s of sediment above tilted fault blocks and half-graben in the central parts of the straits (Johansen et al. 2007), with a thick Palaeogene syn-rift sequence above possible pre-Eocene rocks.

Hall et al. (2009) study focused on the North Makassar Straits where the nature of basement is much less clear. Since the crust beneath the Celebes Sea, just to the north, is oceanic, it is plausible that the North Makassar Straits are underlain by oceanic crust (e.g. Cloke et al. 1999b; Guntoro 1999) but others have put forward arguments in favor of attenuated continental crust (e.g. Burollet & Salle 1981; Situmorang 1982a, b).

Another mechanisms proposed by authors excluding above are (Satyana, 2003): crustal breakdown to the west of South Sulawesi volcanic arc by the Plio-Pleistocene diastrophism (van Bemmelen, 1949), rotation of the continental Southeastern Sundaland, back-arc spreading due to subduction rollback related to India-Eurasia collision at 50 Ma, tectonic escape due to India-Eurasia collision, and mantle delamination by upwelling plume under the Eastern Sundaland. Gunawan and Damayanti (2010) proposed the mechanism of opening of the Makassar Straits as resulted from trans-tensional movement related to WNW/NW - ESE/SE regional strike-slip faults of: Sangkulirang-Palu-Koro, Adang-Lupar and South Makassar Strait. These major faults were tectonic escape due to India-Eurasia collision at around 50 to 40 Ma (Satyana, 2006).

Rifted continental basement underlying the North and South Makassar Straits/Basins are typical in SE Asia sedimentary basins, especially surrounding Sundaland (Figure 2). It should be kept in mind that the Makassar Straits developed in eastern margin of the Sundaland, a continental core in SE Asia. Recent study by Pubellier and Morley (2013) on evolution and boundary condition of SE Asia basins show that most of the basins developed in the continental core of SE Asia (Sundaland) evolved since the Late Cretaceous in a manner that may be correlated to the conditions of the subduction in the Sunda Trench. By the end of Mesozoic times Sundaland was an elevated area composed of granite and metamorphic basement on the rims; which suffered collapse and incipient extension, whereas the central part was stable. This promontory was surrounded by a large subduction zone, except in the north and was a free boundary in the Early Cenozoic. Starting from the Palaeogene and following fractures initiated during the India Eurasia collision, rifting began along large faults (mostly N-S and NNW-SSE strike-slip), which crosscut the whole region. The basins remained in a continental fluvio-lacustrine or shallow marine environment for a long time and some are marked by extremely stretched crust (Phu Khanh, Natuna, N. Makassar) or even reached the ocean floor spreading stage (Celebes, Flores).

New Seismic Data Show Rifted Basement Underlies the Makassar Straits

New seismic data of regional speculative and detailed 2D and 3D surveys acquired by many companies during 2004-2012 clearly show the style of deformation of the Makassar Straits' basement. Rifted basement due to extension in forms of grabens, half-grabens, and horsts generally characterize the basement structure of North and South Makassar Straits/Basins. Basement architecture studies based on seismic data for North Makassar Basin by Nur'Aini et al. (2005) and for South Makassar Basin by Kupecz et al. (2013) show the presence of the rifted basements.

The basement architecture of the North Makassar Basin is characterized by half graben, graben, and horst structures resulted from extension, supported by the presence of clear syn-rift wedges in the hanging walls of extensional faults (Figure 3). The broad basement structure shows rhomboidal shape with the longer axis orientated NNE-SSW. Within that overall shape, however, individual structural lineaments trend predominantly NNW-SSE. Half graben, graben, horst structures and lineaments are arranged in an en-echelon pattern and are parallel to sub-parallel. The faulting has produced a series of disconnected NNW-SSE trending structurally low areas and terminate along strike in accommodation structures/zones such as relay ramps, interlocking fault tips and zones where fault polarity reverses. The extensional fault systems in the North Makassar Basin seem most likely to have formed as a result of oblique rifting (Nur'aini et al., 2005). The principal extension direction is interpreted as east-west, forming an angle of approximately 60° with preexisting faults, resulting in en-echelon pattern (NNW-SSE trending to E-W extension), not orthogonal (90°, N-S trending to E-W extension).

Similar with that of North Makassar Basin, the basement architecture of the South Makassar Basin is also characterized by half graben, graben, and horst structures resulted from extension. The presence of broad Paternoster Shelf, a remnant of

Cretaceous microcontinent (Satyana, 2014) could cause the orientation of rifting in this area is different with that of North Makassar Basin, or they were different in the mechanism of opening. The opening of the South Makassar Basin may similar with East Java Basin to the southwest, which possibly related to backarc basin rifting due to roll-back subduction in Eocene time. Kupecz et al. (2013) identified two phases of extension in South Makassar Basin, pre-Middle Eocene NW-SE extension, and NW-SE Late Eocene extension that continued through the early Oligocene, and possibly into the earliest Miocene. Extension prior to the Middle Eocene resulted in a series of horsts and grabens with a predominant NW-SE orientation. The oldest structural features have this NW-SE trend, including the Pangkat Graben. The biostratigraphic age of the oldest marine sediments within the NW-SE oriented Pangkat Graben is Bartonian, suggesting that the rifting and underlying non-marine deposits occurred by at least 40mya (upper Middle Eocene). Superimposed on the NW-SE structural grain is a younger set of NE-SW faults associated he South Makassar Basin, resulting in a series of graben, half graben, and horst of: Sebuku Graben, Masalima Trough, low areas in South Makassar Basin, Selayar Basin, Pare-Pare Basin; and high areas of Pulau Laut Ridge, Sibaru High, Paternoster Platform, Masalima High, Bone High, and Spermonde Shelf. These series of low and high areas continue southwestward into East Java Basin.

The rifted structures of basement in forms of half graben, grabens, and horst show that the crust beneath the North and South Makassar Straits/Basins to be rifted thinned continental crust. Nur'aini et al. (2005) identified horizon reflections beneath the Top Basement can often be seen suggesting a complex structure more similar to continental basement than oceanic crust. The South Makassar Straits are almost certainly underlain by continental crust (Hall et al., 2009). They are relatively narrow and water depths are mainly 1 to 2 km. There are shelves with thin sedimentary cover above basement to the east and west. Granite and pre-Cenozoic metamorphic rocks are known from boreholes that reach the basement. Recent seismic lines show up to 7 s of sediment above tilted fault blocks and half-graben in the central parts of the straits, with a thick Palaeogene syn-rift sequence above possible pre-Eocene rocks.

Volcanic Basement Penetrated by Rangkong-1 Well

Rangkong-1 well was drilled targeting Eocene-Oligocene carbonate build up growing on horst block in Surumana Block. The well was drilled from 23 February to 14 June 2009 in 2255 meter of water depth. The well did not encounter carbonate build up, but volcanic with 3 meter thick carbonate cap. The well penetrated a top of volcanic at 4345 meter, drilled 140 meters and reached total measured depth of 4485 meter still in volcanic (Figure 4).

Age of the oldest sedimentary rocks overlying altered volcanic could be as old as latest Middle Eocene (foram zone P15, with rare *Truncorotaloides* spp.).

The cuttings of volcanic penetrated by Rangkong-1 were analyzed for: petrographic description of 29 thin sections; major, trace, and rare element geochemistry of 10 samples; magnetic susceptibility of 16 samples; K/Ar dating of 4 samples; 40Ar/39Ar dating of 2 samples; Sm/Nd dating of 3 samples. Attempted to separate zircons for dating and attempted Rb/Sr isochron ages were unsuccessful.

The well cuttings are altered rock (Figure 5). But their original texture sometimes still can be identified. The volcanic basaltic igneous rock that has porphyritic texture (larger phenocrysts surrounded by finer crystals as groundmass, in the cuttings there also abundant of glass) is observed. This glass involvement as hyalophitic texture where the glass begin to envelop the feldspar. The cuttings show that they have medium plagioclase as phenocryst, microlites of plagioclase and glass as groundmass. The glass occupies interspaces between microlites of plagioclase (feldspar) in haphazard orientation is typical in many lavas. Expanding gases in lavas and shallow intrusions often form cavities or vesicles. Usually these vesicles are spherical or ovoid, or have arcuate outlines, but many are highly irregular. They may subsequently be filled with deuteric or secondary minerals, such as opal, chalcedony, chlorite, calcite, and zeolites, to form amygdules. Features of this kind are never found in plutonic rocks.

Geochemistry of volcanic suggests these are andesites contaminated by continental crust (volcanic arcs or rift-related volcanoes) (Figure 6). Major elements were mobilized during secondary alteration. Rare earth and high field strength elements appear to preserve original chemistry. Major and trace elements can provide insight into the degree of alteration, often beyond what can be observed visually. The major element composition suggests that the rocks are quite siliceous (rhyolites), which is due to alteration of original rock composition (andesite). By comparison to major elements (which are often quite soluble), the trace elemental ratios suggest a much more consistent andesite composition. Relatively low degree (~8-10%) of partial melt of primitive sources, or potential crustal contamination, consistent with arc. Compositionally, the Rangkong volcanic rocks could be continental arc rocks or rift related volcanic. Both are similar in that they potentially mix primitive sources with evolved crustal material. Seems consistent with tectonic history of the region. High field strength and rare earth elements suggest that the rocks are significantly altered from their protolith.

K/Ar and 40Ar/39Ar ages appear to be affected significantly by secondary alteration therefore the ages are unreliable. Sm/Nd ages are not very precise, but they indicate an Eocene emplacement age for the volcanic edifice, in good agreement with biostratigraphy of oldest sedimentary rocks, seismic data, and regional geology. Best estimate of age of Rangkong volcanic is from 4394-4399 meters, and supports an Eocene eruption (57 ± 20 Ma). Nd geochemistry also supports derivation from a mixture of primitive (mantle) magmas and Proterozoic continental sources. Appears that the 4393-4399 sample was derived or contaminated by ~1300-1600 Ma crustal rocks. Isotope geochemistry suggests a mixed primitive and crustal continental source (not MORB or oceanic crust).

Volcanic Basement Penetrated by Kaluku-1 Well

Kaluku-1 well was drilled targeting Eocene-Oligocene carbonate build up growing on horst block in Kuma Block (Figures 7 and figure 8). The well was drilled from 3 May to 5 October 2011 in 1491 meter of water depth. The well did not encounter carbonate build up, the well was deepened penetrating Eocene clastics and had a TD on weathered volcanic at 5291 meter. The well encountered two Eocene sandstone intervals containing oils.

The volcanic on TD is tuff, based on mud log the tuffs were described as: very light to light grey, white, light grey to light bluish grey, with common medium to dark grey mottling, also commonly speckled with very fine opaque (mafic?) material, also mottled with 20-30% of light red to reddish brown (abundant altered), generally blocky, soft sticky and hydrated to moderately firm, with common floating dark grey opaque / mafic flecks and phenocrysts in plagioclase groundmass, locally showed interlocking between altered mafic mineral and altered plagioclase, rare traces of pyrite, non-calcareous. On petrographic analysis these tuffs described as shales. The shales are considered resulted from weathering of tuffs.

This differs with claystone overlying the tuff which were described as medium to dark grey, medium to dark greenish grey, also very dark grey to greyish black in part, firm to moderately hard, sub blocky to blocky, sub fissile to fissile in part, earthy luster, commonly waxy, also slightly silty in part, sub splintery in part, non-calcareous.

The cutting samples were analyzed for biostratigraphy, petrography, X-ray diffraction, reservoir analysis, geochemistry, and K-Ar dating.

The tuffs described on mud log were petrographically analyzed as composed dominantly of shales (65-70 %) with subordinate loose grains and recrystallized limestone (Figure 9). Based on petrographic analysis shales are massive to laminated, variably silty to sandy, locally sideritic, in which the grains are randomly carried in the matrix and consist of quartz, metaquartzite, untwined feldspar, organic material, and zircon. Detrital clay has been partly replaced by microcrystalline siderite. Some shale cuttings have been fully replaced by microcrystalline siderite. Siderite occurs as a replacement of former clay matrix and sometimes shows spherulitic structure. Pyrite occurs as very fine to fine framboidal and anhedral crystals disseminated in the matrix and in association with organic material. Minor non ferroan and ferroan calcite occur as replacements of grains. No visible porosity. The loose grains consists of quartz, pyritized organic material, and blocky calcite. Recrystallized limestone classified as crystalline. No visible porosity.

The results of the XRD analysis on TD cuttings show that that the mineralogy of the washed residues of ditch cuttings comprises clays 44%, quartz 40%, and siderite 2%. The clays are kaolinite and chlorite. The XRD mineralogy did contain minerals indicative of the presence of a volcanic rock.

The cuttings on TD were analyzed for biostratigraphy using nannofossil zonation, planktonic foraminifera zonation, larger foraminifera letter stage, and palynology zonation. No fossil encountered, therefore the biostratigraphic age and paleoenvironment of the cuttings are indeterminate.

The K-Ar absolute dating were conducted for "volcanic basement" penetrated by Kaluku-1 well from 17,200 to 17,360 ftMD. The K-Ar dating is 65.0 Ma ± 2.1 Ma for the sample at 17,200-17,300 ft, equivalent to an Early Paleocene, Danian age. The K-Ar absolute dating for the sample at 17,340-17,360 ft is 67.1 Ma ± 2.6 Ma, equivalent to a Late Cretaceous, Maastrichtian age. The two samples are very closely dated within the range basal Tertiary to topmost Cretaceous. Taking into consideration that the top of the Cretaceous is at 65.5 Ma and that the possible analytical error is >2.0 Ma, both samples may be of more or less the same age, whether basal Tertiary or topmost Cretaceous. This agrees with regional geology of the area. The age of the cuttings shows pre-rifting basement, where the rifting itself initiated in Early Eocene in this area based on biostratigraphy of the oldest sediments overlying the basement.

Petrographic composition of shales at TD of Kaluku-1 well as composed by quartz, metaquartzite, zircon; the loose grains also consists of quartz,; and based on XRD analysis on TD cuttings show that that the mineralogy of the washed residues of ditch cuttings comprises clays 44% and quartz 40% show that protoliths of tuffs, weathered to shales, are related to continental crust.

The presence of detrital zircon in volcanic shale is interesting. Zircon is ubiquitous in the crust of Earth. It occurs in igneous rocks (as primary crystallization products), in metamorphic rocks and in sedimentary rocks (as detrital grains). Zircon is a common accessory to trace mineral constituent of most granite and felsic igneous rocks. Due to its hardness, durability and chemical inertness, zircon is known to survive numerous sedimentary cycles, metamorphism and diagenesis, and is a common constituent of most sands. Zircon is rare within mafic rocks and very rare within ultramafic rocks (Deer et al., 1982). Based on this, granitic continental crust deep beneath the Makassar Straits could source the detrital zircon. Recently, zircon geochronology (U–Pb dating of zircons) provides compelling evidence for the presence of a continental fragment of Gondwana affinity, ages ranging from Proterozoic to Archean (Smyth et al., 2007; van Leeuwen et al., 2007; Satyana, 2014) within the deep crust of SE Sundaland. This fragment was sampled by melts feeding Early Cenozoic. In Sulawesi continental rocks have been reported (van Leeuwen et al., 2007) Geochemical and zircon dating evidence from the Malino Metamorphic complex of northwest Sulawesi reveals the presence of Archean material with ages up to 3500 Ma.

Oil in Eocene Section of Kaluku-1 Well

Hall et al. (2009) in discussing the nature of the basement lies beneath the North Makassar Straits concluded that they cannot agree on the nature of the basement beneath the straits whether continental or oceanic, and similar disagreement is likely to continue amongst those working in the area. Hall et al. (2009) considered that the character of the basement beneath the Makassar Straits is important for the petroleum system since it will determine the subsidence history, thermal history and, consequently, source-rock maturation, as well as the style of traps. If continental, it is likely there are Eocene lacustrine source rocks, tilted fault blocks and carbonate and clastic reservoirs. If there is oceanic crust beneath the Makassar Straits, Miocene organic material transported into deep water would probably be required for the petroleum system to work.

What is mentioned by Hall et al. (2009) occurred with Kaluku-1 well when the well accidentally discovered oils in Eocene section which was not targeted on the prognosis. The oils were sourced by lacustrine source rocks, directly proving that the basement of North Makassar Straits is continental. No lacustrine develop on oceanic crust.

Kaluku-1 well was drilled by ConocoPhillips in Kuma Block in 201, targeting Miocene reef. The well penetrated the anticipated Recent through to Late Miocene clastic fold-belt section down to a significant detachment the top of which was encountered at 14248 ft (4343 m) TVD, in excess of 2000 ft (around 600 m) deep to prognosis. The objective Miocene reefal carbonate was not present immediately below the detachment as had been anticipated, rather a 500 ft (around 150 m) sequence of massive homogeneous Eocene shales was encountered. A 27 ft interval of argillaceous limestone was encountered from 14893 to 14920 ft at the base of this Eocene shale and in the absence of information to the contrary, this was assumed at the time to be the Miocene reef. The 11-7/8" liner was run at this time in anticipation that the next hole section would penetrate the objective carbonate. The sections penetrated in the 10-5/8", 8-1/2 and 6" hole sections from 14920 ft to TD at 17360 ft MD comprised interbeds of shales, thin limestones and occasional thin but clean sands with excellent reservoir character. This section has been age dated as Eocene. Live but very waxy oil was recovered on wireline from sands at 15752 ft (4801 m) and 16702 (5091 m) ft MD.

The oil recovered in wireline chambers at both 15752 ft and 16702 ft MD was highly waxy and solid at room temperature (Figure 10). The laboratory analysis shows API of 25.5 at 60º F and pour point of 110º F from 15752 ft oil sample, its sulfur and wax contents are 0.060 and 21.09 % wt, respectively. Oil from 16702 ft MD shows API of 29.6 at 60º F, pour point 113 º F, sulfur content 0.102 % wt, wax content 17.23 % wt.

The estimates for static bottom hole temperature to be of the order of 340º and 365º F at the two oil recovery depths. The waxy nature of the oil suggests a lacustrine source. The petrophysical evaluation of Kaluku-1 indicates a total of 190 ft of net sand through the Eocene sediments with porosity averaging 24.4%. The highest porosity in the well is interpreted to be 35% at a depth of 16216 ft, in excess of 11,000 ft below the mudline.

Two oil samples recovered by RCI (reservoir characterization instrument) at depths 15752 ftMD and 16702 ftMD were characterized. Liquid chromatography analysis results indicate that the oils are paraffinic crudes mature with a high abundance of saturates. High temperature gas chromatography results indicate both crudes can be classified as heavy waxy oils (n-alkanes exist up to nC_{90}). The high levels of normal alkanes indicate that these oils were sourced from aquatic sub-oxic sediments (Pr/Ph 2.48 for RCI-1 and 2.25 for RCI-2) (Figure 11). This suggests derivation from a fresh water lacustrine facies. A plot of pristane/nC_{17} and phytane/nC_{18} suggests that the source is a mixed Type II and III kerogen facies. GC-MS results show that the RCI-1 oil was generated from a mature source rock deposited within a terrestrial environment with algal input. The RCI-2 oil was generated from a more algal-dominated source (shallow lacustrine).

Stable carbon isotope values were determined on the saturate and aromatic fractions for the two RCI oil samples (recovered from depth 15752 ftMD and 16702 ftMD). Results indicate that the oils can be categorized as isotopically 'heavy' (saturates -23.93 ‰, aromatics -19.25 ‰ for RCI-1, and saturates -20.25 ‰, aromatics -20.10 ‰ for RCI-2). A plot of the carbon isotope data on Sofer's diagram shows that the RCI-1 crude is situated in the region assigned to oils of "terrestrial" origin. The Canonical Variables for this oil sample (CV 6.16) supports this interpretation. The RCI-2 crude has a high Canonical Variables (-5.04) which suggest derivation from a non-marine algal source.

Biomarkers present in these oils have been analyzed by computerized Gas Chromatography-Mass Spectrometry performed on saturate and aromatic fractions. Information pertaining to the organic origin of these oils have been primarily gleaned from saturates biomarkers and, in particular, the triterpane and sterane classes of compounds. A review of these results has highlighted the following salient characteristics.

Triterpanes including hopanes (m/z 191) fragmentograms for the RCI-1 crude sample displays relatively simple distributions of bacterially-derived 17αβ (H)-hopanes where C30 hopane is relatively high to C29 norhopane, showing shaly source rocks (Figure 11). The triperpane suggests that these oil samples have been derived from a mixed terrestrial higher land plant and algal source. Both crude oils show a lower abundance of the C_{19} and C_{20} tricyclic compounds (B and C) relative to the C_{23} tricyclic compound (F). This indicates a lacustrine algal origin. The 18α (H)-Oleanane peak is relativity very low in both samples and suggests limited terrestrial input.

Steranes (m/z 217) distributions for both oil samples show a full suite of normal steranes with the C27ααα(R) forms less abundant (28.17 % at RCI-1 and 37.87 % at RCI-2) relative to the C29ααα(R) steranes (59.92 % at RCI-1 and 42.65 % at RCI-2) (Figure 11). This implies RCI 1 has a significant contribution of terrestrially-derived organic matter. The RCI-2 shows a significant contribution of mixed terrestrial and algal organic matter. A plot of the sterane distributions on Huang and Meinschein's paleo-environment diagram shows that the samples are situated in the region assigned to oils of "Estuarine or Shallow Lacustrine origin".

Assessment of the thermal maturity of the oil at time of generation/expulsion has relied upon saturate and aromatic biomarker maturity-specific parameters. The Methylphenanthrene Index has been calculated from the distribution of phenanthrene (m/z 170) and methylphenanthrenes (m/z 192) in the oils. The RCI 1 and 2 oils show relatively low MPI-1 values (0.28 at RCI 1 and 0.45 at RCI 2) suggesting the RCI-1 oil was generated at marginally mature levels based on calculated vitrinite reflectance (Rc) equivalent data of 0.57 % Ro, and the RCI-2 oil generated at 0.67% Ro. The

Ts/(Ts+Tm) ratio is a reliable maturity indicator and is measured using m/z 191. The Tm/Ts ratio at RCI-1 oil is 0.44, and 0.38 at RCI-2, these ratios suggest the oils were generated at around 0.70% Ro for both oils.

Based on the biomarker distributions, these oils are interpreted to have been derived from a source rock facies deposited in shallow lacustrine with some terrestrial material inputs. Oil geochemistry strongly proves that the basement of North Makassar Straits is continental, forming rifted structures as grabens and horsts where lacustrine sediments were deposited within the grabens and had inputs from terrestrial deposits from adjacent horsts.

The presence of a lacustrine water body is determined by both the presence of a topographic depression and the availability of water to fill it. The depression may form through numerous processes. Tectonically derived lakes are the most significant with respect to source rock development (Katz, 1991). Furthermore, lake basins formed in extensional regimes (i.e., grabens, pull-aparts) commonly have low maximum width/maximum depth ratios. These ratios play a role in organic preservation potential by affecting the ability of the wind to mix the water column. Lower ratios tend to support greater water column stability. However, it should further be noted that even in these narrow troughs the relative rate of subsidence compared to sediment influx is important in maintaining the presence of a deep lake with a low width/ depth ratio. In those situations where the rate of sediment influx is comparable to the rate of subsidence, available organic matter is diluted and source rock potential is reduced. If the influx of sediment is great enough, the lake will actually be replaced by a swamp or bog and coal will develop. These sediments may act as an excellent gas source. In contrast, when the rate of subsidence is greater than the sediment influx, a deep lake can develop and high-quality oil source rocks may form. In general, maximum source rock deposition occurs during the period of maximum subsidence.

Commonly, in many graben systems it has been observed that initial subsidence rates are low compared to those of sedimentation (Katz, 1991). In such situations the initial sedimentary fill represents a shallow water facies. This initial phase is followed by a period when there is an increase in the rate of subsidence relative to sedimentation, leading to the subsequent development of deep lacustrine facies. During the more mature phases of graben development, sedimentation rate usually begins to increase relative to subsidence and a shallow water lacustrine phase once again becomes established, resulting in the final lake fill succession which may include the development of a coaly sequence.

DISCUSSION

This study is the first publication on basement geology based on hard data of wells penetrating the basement. Basement here is rock formation (volcanic rocks, altered, weathered, or unaltered) underlying oldest sedimentary sequence in the North Makassar Basin. In this case the basement horst becomes the site where rifting volcanic developed. Deep basement is remained unpenetrated by any well. However, characteristics of volcanic may reveal the nature of deep basement, since some materials of the basement are incorporated in the basement. The presence of oils in Eocene section overlying the basement also reveal the characteristics of the basement.

The cuttings of volcanic penetrated by Rangkong-1and Kaluku wells were analyzed for: petrographic description; major, trace, and rare element geochemistry (petrochemistry); magnetic susceptibility; geochronology using K/Ar dating, 40Ar/39Ar dating, Sm/Nd dating of 3 samples. Weathered shales from tuff were analyzed for biostratigraphy, petrography, X-ray diffraction, geochemistry, and K-Ar dating. The oils in Eocene section were analyzed for bulk properties, carbon-13 isotope and biomarker analysis. The results of all analyses have been discussed above. These new data make a firm constraint for understanding the nature of basement of the Makassar Strait and how its rifting history. Combination with newly acquired seismic data and examination of formation model from previous studies may reveal the rifting history of the Makassar Straits more definitely.

Gondwanan Microcontinent as the Basement of the Makassar Straits

Eastern part of Kalimantan and western part of Sulawesi formed a single area in the Late Mesozoic (e.g. Katili 1978; Hamilton 1979). In the light of terrane tectonics the area was part of microcontinent/s. The microcontinents have been named, proposed and interpreted in some various ways, such as: Paternoster (Situmorang, 1989; Hutchison, 1989; Metcalfe, 2013), Paternoster-Kangean, including West and South Sulawesi (Manur and Barraclough, 1994; Parkinson et al., 1998; Wakita, 2000; Satyana, 2003, 2010a), Bawean (Smyth et al., 2007; Metcalfe, 2013), East

Java (Bransden and Matthews, 1992; Sribudiyani et al., 2003; Smyth et al., 2007; Deighton et al., 2011; Metcalfe, 2013), East Java-Makassar Straits (Parkinson et al., 1998; Emmet et al., 2009; Granath et al., 2009), Argoland (Hall et al., 2009).

The microcontinents in this area were added to rim of the Sundaland during the Late Cretaceous in East Java and West Sulawesi (Smyth et al. 2007; van Leeuwen et al. 2007). Recent paper by Satyana (2014) (Figure 12) based on the geology of western part of Sulawesi argued this collision took place in mid-Cretaceous time, at around 100 Ma. The Meratus suture is the remnant of the collision. Outboard of the Meratus suture, East Java and West Sulawesi are underlain in part by Archaean continental crust, and geochemistry and zircon dating (Smyth et al. 2007; van Leeuwen et al. 2007) indicate a west Australian origin or Gondwanan microcontinent. These microcontinents separated from NW Australia (Gondwanan) in the Late Triassic–Late Jurassic by opening of the Ceno-Tethys and accreted to SE Sundaland by subduction of the Meso-Tethys in the Cretaceous (Metcalfe, 2013).

The Cretaceous arrival of continental fragments contributed to crustal thickening, magmatism, emergence and widespread erosion of Sundaland during the Late Cretaceous and Early Cenozoic, thus further diminishing the completeness of the stratigraphic record. Of greater importance for basin development was the considerable variation in basement lithologies and structure, which gave Sundaland at the beginning of the Cenozoic a highly complex basement fabric that varies from area to area, and which includes profound and deep structural features that have been reactivated at different times in different ways. This complex basement structure is the important influence on the formation and character of the sedimentary basins of Sundaland.

The microcontinents formed deep basement of the Makassar Straits. Nd geochemistry of Rangkong-1 supports this by derivation from a mixture of primitive (mantle) magmas and Proterozoic continental sources as shown by 4393-4399 m depth sample derived or contaminated by ~1300-1600 Ma crustal rocks. The presence of detrital zircon in volcanic basement of Rangkong-1 and Kaluku-1 may be sourced by granitic continental crust deep beneath the Makassar Straits. Attempts to separate zircons for dating in Rangkong-1 well was unfortunately not success. To the southwest and east of the North Makassar Straits, (East Java and Sulawesi onshore, respectively), recent analysis on zircon geochronology (U–Pb dating of zircons) provides compelling evidence for the presence of a continental fragment of Gondwanan affinity, ages ranging from Proterozoic to Archean (Smyth et al., 2007; van Leeuwen et al., 2007; Satyana, 2014) within the deep crust of SE Sundaland. Geochemical and zircon dating evidence from the Malino Metamorphic complex of onshore Sulawesi reveals the presence of Archean material with ages up to 3500 Ma - van Leeuwen et al., 2007).

Rifting History of the Makassar Straits

Rifting history of the Makassar Straits began with Late Cretaceous to Eocene volcanism in the area of microcontinents (Paternoster and West Sulawesi) where the straits would developed later (Figure 12). During the Late Cretaceous the microcontinents remain formed the deep basement of the Makassar Straits. Renewed subduction occurred behind the microcontinents which initially a passive margin (Satyana, 2014). The change of passive margin to active margin is considered due to “chocking” of the microcontinents to the Meratus Trench. This chock/collision had stopped the drifting of the microcontinents and spreading of oceanic plate behind it. To compensate tectonically this chocking, the uppermost part of oceanic plate in front of Paternoster was detached and obducted, the oceanic plate behind Paternoster due to continuing spreading by ridge push, changed from passive margin to become subduction zone.

The subduction zone resulted in partial melting flowed up through Paternoster-West Sulawesi and triggered Late Cretaceous volcanism. Volcaniclastic deposit of Pitap and Haruyan Group in SE Kalimantan with its granitic to dioritic intrusion dated 73-68 Ma (Heryanto, 2010) and andesitic lava of Pitanak Formation dated 83-66 Ma (Sikumbang, 1986); tuff and tuff breccia; or volcanic basement penetrated by Kaluku-1 well as 65.0 Ma ± 2.1 Ma for the sample at 17,200-17,300 ft, and 67.1 Ma ± 2.6 Ma for the sample at 17,340-17,360 ft equivalent to a Late Cretaceous-Paleocene (Maastrichtian-Danian stage); related to this activity. The K-Ar absolute dating on post-collision radiolarian chert of Bantimala, South Sulawesi (Wakita et al., 1996) recording the intercalation of rhyolitic tuff layers along the Pateteyang River may be partly contemporaneous with the Haruyan volcanics (Wakita, 2000). During Paleocene to Eocene calc-alkaline volcanism activity still took place in South Sulawesi (Yuwono et al., 1988;

Soeria-Atmadja et al., 1998). These suggest that subduction-related magmatism occurred along the southeastern margin of Sundaland at this time (Soeria-Atmadja et al., 1998). Sm/Nd ages of Rangkong-1 volcanics, indicating an Eocene emplacement age (57 Ma) for the volcanic edifice, and some tuffs in Kaluku-1 basement also may relate to this.

Rifting of the Makassar Straits initiated after this volcanism as part of the eastern rim of the Sundaland which suffered collapse and incipient extension (Pubellier and Morley, 2013) (Figure 13). From a number of mechanisms ever proposed, the collapse or incipient extension of the Makassar Straits could morelikely be resulted from two mechanisms: tectonic escape following collision of India to Eurasia and/or backarc rifting due subduction rollback related to slower rate of subduction as response to the collision of India to Eurasia (Satyana, 2010b).

Following the collision of India to Eurasia in 50 Ma, Southeast Asia became the area of post-collision tectonic escape (Tapponnier et al., 1982). Almost the whole SE Asia escaped extruded southeastward away from the collision. Major strike-slip faults and opening of marginal basins occurred as responses to the escape tectonics. Gunawan and Damayanti (2010) detailed the mechanism of how the Makassar Straits opened due to trans-tension movement by three regional strike-slip faults across the straits: Sangkulirang-Palu-Koro, Adang-Lupar, and South Makassar Strait Faults. A series of pull-apart depressions related to strike-slip faulting were resulted from this movement.

Subduction roll back due to slower rate of subduction related to collision of India into Eurasia possibly initiated the rifting in back-arc position including the Makassar Straits (Figures 13 and 14). Regionally for Sundaland, Pubellier and Morley (2013) showed starting from the early Paleogene and following fractures initiated during the India Eurasia collision, rifting began along large faults (mostly N-S and NNW-SSE strike-slip), which crosscut the whole region. The basins remained in a continental fluvio-lacustrine or shallow marine environment for a long time and some are marked by extremely stretched crust (Phu Khanh, Natuna, North Makassar) or even reached the ocean floor spreading stage (Celebes and Flores). Western Sundaland was a combination of basin opening and strike-slip transpressional deformation. Whereas, the configuration suggests a free boundary particularly to the east (trench pull associated with the Proto-South China Sea subduction; Java-Sulawesi trench subduction rollback – including the Makassar Straits).

Rifting of the Makassar Straits were clearly shown on seismic sections. The undisputed graben and half-graben seen in parts of the straits mapped by Nur'aini et al. (2005) indicate extended continental crust. Extension began in the Middle Eocene and formed graben and half-graben above which is an important unconformity of probable Late Eocene age. The principal extension direction is interpreted as east-west, forming an angle of approximately 60° with preexisting faults, resulting in en-echelon pattern (NNW-SSE trending to E-W extension). The unconformity marks the top of the syn-rift sequence. Structures can be seen beneath the unconformity which could be carbonate build-ups on tilted fault blocks or volcanic edifices. Rifting due to thermal uplift may continue during the Oligocene.

Similar with North Makassar Basin, the basement architecture of the South Makassar Basin is also characterized by half graben, graben, and horst structures resulted from rifting. The presence of broad Paternoster Shelf could cause the orientation of rifting in this area is different with that of North Makassar Basin. The opening of the South Makassar Basin could related to rifting of the basement in East Java Basin to the southwest, which possibly related to backarc basin rifting due to roll-back subduction in Eocene time.

The observed subsidence in well data and on reflection profiles from the Makassar Basins appears to be compatible with those produced by the simple instantaneous extension of the lithosphere as envisaged by the stretching model of McKenzie (1978, in Situmorang, 1981). The formation of the basin started with rifting in Lower-Middle Eocene or probably earlier, and continued until the Lower Miocene. 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 (maximum present depth almost 2.5 km), it is believed that spreading, - as in the sense of Atlantic type margins has not yet been developed in the

Makassar Basin. The Basin is underlain only by a thinner continental crust compared with the surrounding areas. This has been proved by Rangkong-1 and Kaluku-1 wells penetrating the basement as discussed above.

Rifting of North and South Makassar Straits ceased by the end of Lower Miocene (Situmorang, 1982), failed to develop further into sea-floor spreading (Figure 13). The cause was collisions of microcontinents to the east of Sulawesi in Neogene time, firstly by collision of Buton-Tukang Besi microcontinent in Early-Late Miocene and secondly by collision of Banggai-Sula microcontinent in Middle Miocene-Pliocene time (Satyana and Purwaningsih, 2011). Following the cessation of rifting (failed rift system), the basin underwent subsidence (sagging) due to thermal subsidence in the Early Oligocene to Late Miocene resulting in deep-water North and South Makassar Basins. Since then the sediments have been deposited continuously across the basin without significant deformation. Deepening of the basins also related to flexural subsidence due to loading on the west and east sides of the Makassar Straits, as inversion in eastern Kalimantan migrated east and the influx of Mahakam delta prograded east since the Early Miocene, while folding and thrusting of western Sulawesi migrated west since the Early Pliocene. This compressional event is considered to be a major force for creating the foreland basin in the basins (Hall et al., 2009). East-west seismic lines clearly demonstrate the westward vergence of the fold and thrust belt system. The new seismic data also show that the folding and uplift was initiated in the Early Pliocene. It is therefore interpreted that the North Makassar Straits Basin became a foreland basin no earlier than Early Pliocene and it continues as such today.

Exploration of West Sulawesi Offshore Area

Western part of the Makassar Straits to the east of Kutai Basin where Mahakam deltaic sediments have been deposited since the Miocene, and continued into its deepwater facies where transported deltaic materials were deposited, have been proven as very prolific petroleum province in Indonesia. The area is the biggest gas producer in Indonesia and also significant for its oil production. Older than Miocene, the objectives are too deep for petroleum exploration and production due to burial by very thick deltaic deposits. The Paleogene objectives of the Makassar Straits should be explored in the eastern part of the Makassar Straits or the West Sulawesi Offshore area (Figure 15).

The West Sulawesi Offshore was intensively explored by many companies from 2008 to 2012. There were 13 exploration wells drilled with two wells discovered petroleum (technically success). Satyana et al. (2012) summarized the updated exploration in this area. The first well in the region, Rangkong-1, was drilled by ExxonMobil Surumana in 2009. The well failed to find hydrocarbons. ExxonMobil moved to their other block, Mandar Block to the south, and drilled three wells called Sultan-1 (2009), Kris-1 (2010), Kris-1 ST (2010). Sultan-1 discovered uneconomic mixed gas (biogenic and thermogenic). 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 the 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. The turn then came to ConocoPhillips in Kuma Block, they drilled the Kaluku-1 well (2011) and accidentally discovered oils in non-objective Eocene sandstones. 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 well was dry. The last three 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), Anoman-1 (2012), and Antasena-1 (2012). The wells were dry due to reservoir problem and no charging. Satyana et al. (2012) evaluated that most of the wells are dry because problems of geochemical risks (very limited or no source in low areas prognosed as kitchens, immaturity, recent generation/too late generation, migration barriers and minimal volumes).

Rifted grabens or low areas formed when western part of Sulawesi separated from Eastern Kalimantan are not always kitchens (generating source pods) (Figure 15). 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 northern part of North Makassar Strait in this area which could be too rapid. Significant extension usually results in rapid subsidence that potentially causes an absence of coaly or lacustrine, syn-rift source rocks. Hence the entire syn-rift section could be marine or sufficiently diluted reducing the organic richness. 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, to the south, the Makassar Basin opening was slower than its northern counterpart, providing better source due to small possibility of diluting organic richness.

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 would be late in petroleum generation compared to blocks located near the Sulawesi onshore 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 for maturity of Paleogene sources, the maturity would follow 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 section is dominated by volcanic-clastic deposits, (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. 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 part of the North 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.

Further Exploration Implications after Kaluku-1 Oil Discovery

Oil discovery by Kaluku-1 well in Kuma Block is very significant for the prospectivity of Paleogene objectives in the Makassar Straits. It is the first discovery of petroleum in Eocene objective at rifted structure of the Makassar Straits. Most of the wells drilled in West Sulawesi Offshore targeted Oligocene carbonate build up growing on horst block of rifted basement. Kaluku-1 well was also proposed to test this objective in Kuma Block. The carbonate build up was not present, the well was deepened and accidentally encountered oils in Eocene sandstones deposited on the horst block. These sands displayed excellent reservoir character with porosities as high as 30% and averaging in excess of 27%. The oils are interpreted to have been derived from a source rock facies deposited in shallow lacustrine within the graben (Syn-rift) with some terrestrial material inputs shed from the horst block. The oils came from early generation with calculated Ro of 0.57-0.67 %.

A total of one hundred twenty-nine handpicked cuttings samples of Kaluku-1 comprising medium light grey claystones inter-bed with greyish red claystones were analyzed from Middle Eocene section from 14430 ftMD to 17120 ftMD. Geochemical log of source samples is displayed on Figure 16. The organic richness levels recorded for this section are negligible to excellent (0.05-4.12

wt% TOC). The corresponding Rock-Eval pyrolysis data suggest these samples have poor to excellent hydrocarbon source potential (S1+S2 as 0.11-18.94 mg HC/gm rock). Low to high Hydrogen Indices (52-467) indicate variable oil and gas source potential (Type I to III). The lowermost section of the well (not older than Early Eocene), interval 17120 ftMD to 17360 ftMD/TD comprises brownish black claystones interbedded with medium grey volcanic sediments. The organic richness levels recorded for this section are poor to very good (0.35-2.96 wt% TOC). The corresponding Rock-Eval pyrolysis data suggest these samples have poor to good hydrocarbon source potential (S1+S2 as 0.96-6.95 mg HC/gm rock). Moderate to high Hydrogen Indices (188-334) indicate oil and gas source potential. Vitrinite reflectivity values recorded for the lowermost section below the unconformity, increase steadily from 0.52 %Ro (marginally mature) at depth 14450 ftMD to 0.77 %Ro (mid-mature) at depth 17360 ftMD (Figure 5). These results suggest that sediments below the unconformity are early mature to mid-mature to generate oil. Tmax values recorded in this well increase steadily from 421°C (immature) at depth 8010 ftMD to 455°C (mid-mature) at 17200 ftMD and are consistent with the VR data.

Two reservoirs containing oils are very good to excellent in quality. The reservoirs have average porosities 30 % and permeability 450-500 mD (Figure 10).

The above discussions show that petrophysical characteristics of Eocene oil-bearing sandstones and geochemical characteristics of Eocene shales penetrated by Kaluku-1 well are very good to excellent. This obviously will affect regional prospectivity of Eocene objective in this area. The shales were deposited on horst block which usually is an area with no good organic preservation because of oxic condition. However, the geochemical characteristics show that the shales have good, very good, to excellent quality. The better quality of the source rocks will be in the graben area, in deep lacustrine system which is unexplored so far in this area. This area is considered to develop to the east of Kaluku-1 discovery where thicker tectonic loading/burial of Neogene fold-thrust belt of West Sulawesi Offshore is obtained (Figure 17). The thicker the burial the earlier the oil generation. The earlier the oil generation, the more the volume of charging. The thicker sandstone reservoir may exist to the east of the site Kaluku-1 well because the sands were sourced from Sulawesi.

The Kaluku-1 well warrants further exploration in this area, focusing on deep Eocene objective (Syn-rift play) the available seismic data is not enough in quality to continue further exploration for deep target. The existing seismic data cannot be used to condemn the area as uneconomic. The area needs new seismic data, 3-D or high resolution 2-D covering the area to the east of Kaluku and around, including transition zone area with onshore Sulawesi. The oils discovered by Kaluku-1 obviously reveals there is active petroleum system in this area. Further exploration of West Sulawesi Offshore should target Eocene clastics in rifted horsts and grabens of West Sulawesi Offshore.

CONCLUSIONS

1. Hard data consists of the basement of the Makassar Straits penetrated by Rangkong-1 and Kaluku-1 wells, and oils in its Eocene section discovered by Kaluku-1 well constraint that the basement of the Makassar Straits is Gondwanan Paternoster-West Sulawesi microcontinent, thinned due to rifting from the Early/Middle Eocene to Early Miocene time as response to back-arc rifting related to subduction roll back in SE Sundaland. The Eocene rifted grabens and horsts are the sites for shallow lacustrine sources, sandstone reservoirs, and traps.

2. The oils have been discovered in Eocene section of the West Sulawesi Offshore. Based on Kaluku-1 discovery, further exploration should target the area to the east of Kaluku discovery until transition zone with Onshore Sulawesi. Here the source rocks are considered to be thicker, better quality, earlier maturation hence generating more oils. The sandstone reservoirs will also be thicker. New 2D high resolution or 3D seismic data will be required for better evaluation. Dry wells drilled here by various operators from 2009-2012 did not condemn the area. All of the wells did not target the Eocene section on rifted structures that actually should be.

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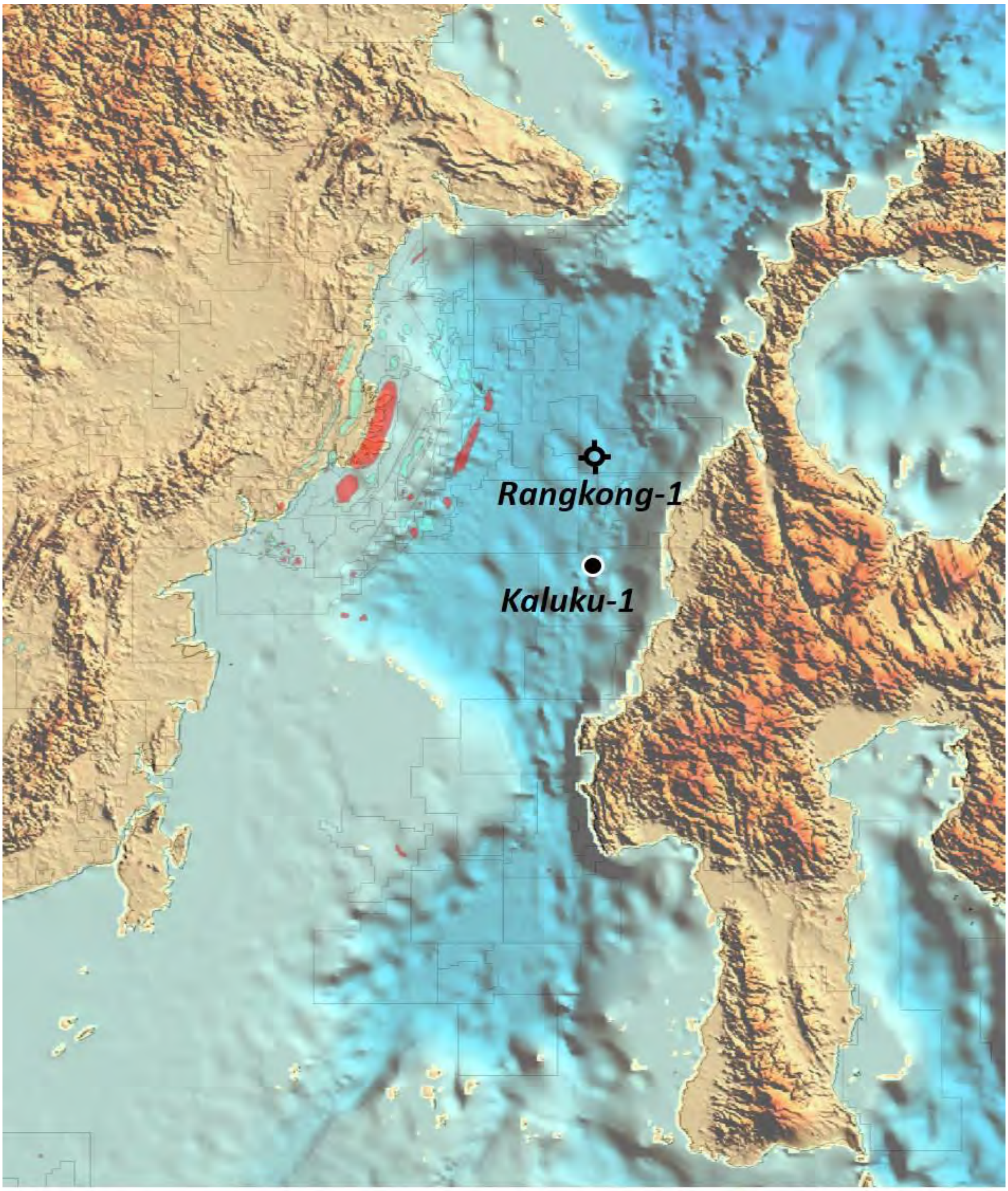


Figure 1 - The Makassar Straits are located between Kalimantan and Sulawesi Islands. The straits include North Makassar Basin and South Makassar Basin. The location of wells discussed in detail in the paper are shown (Rangkong-1 and Kaluku-1). The locations of oil and gas fields (red colour) are indicated.

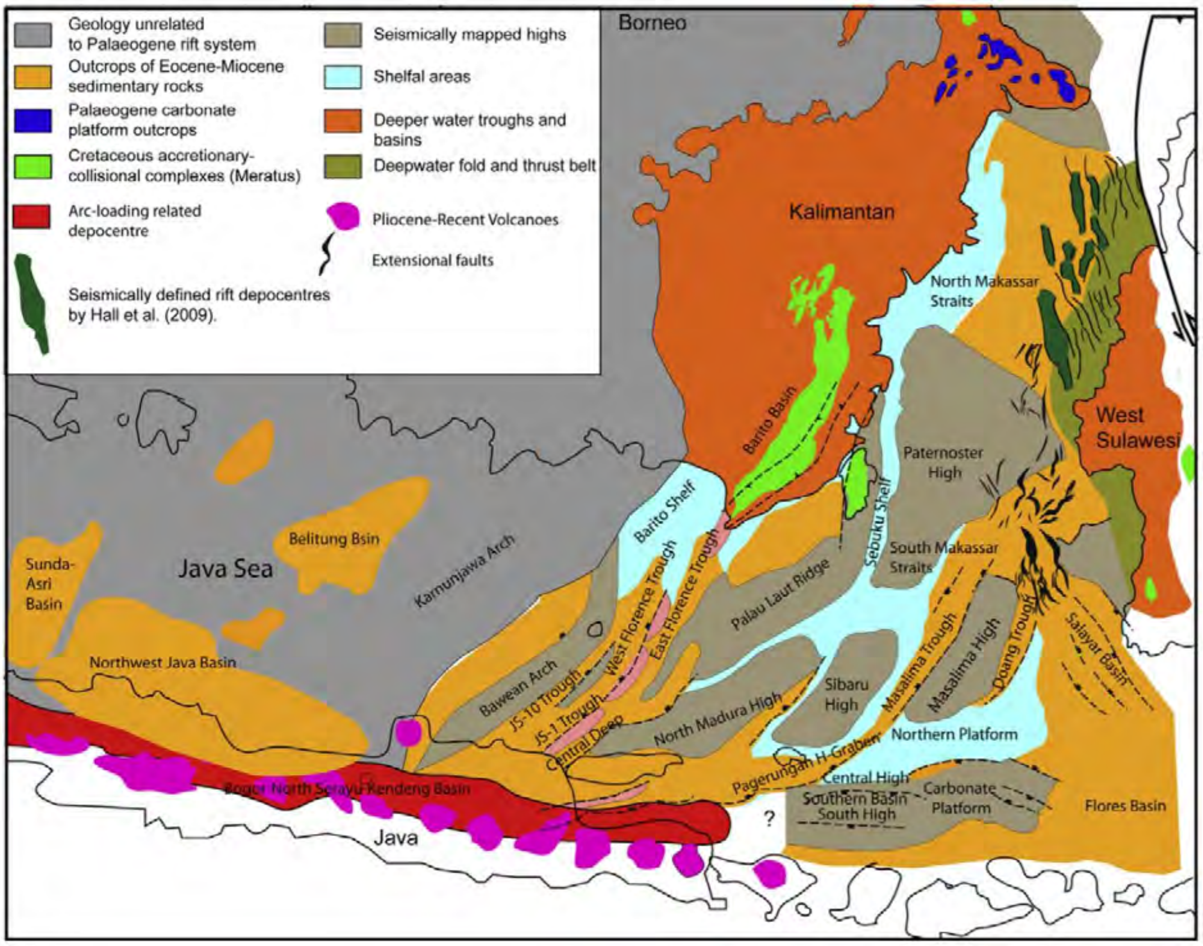


Figure 2 - Structural map of the major ridges and basins of South Sundaland from SE Kalimantan to Eastern Java and Flores basins (after Pubellier & Morley, 2013).

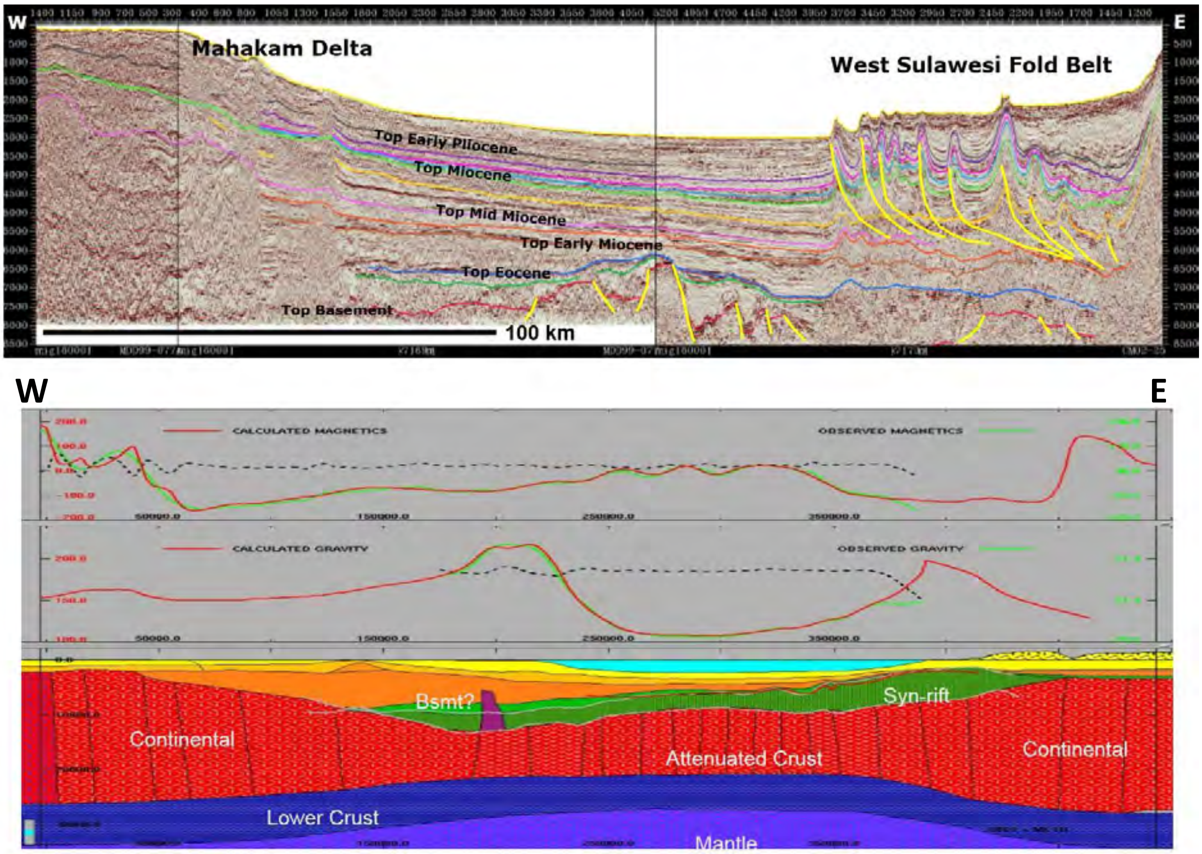


Figure 3 - Above – Regional seismic section across the Makassar Straits from Mahakam Delta to West Sulawesi Foldbelt. The section shows rifted basement resulting in horsts and grabens in the Paleogene, and sagging since the Early Miocene onward. On the west side is very thick Neogene deltaic sediments of Mahakam with obvious diapirs. On the east side is foldthrust belt of West Sulawesi deformed in thin skinned-tectonic style with Early Miocene detachment. Below - Gravity and magnetic measurement across the Makassar Straits with model of crustal architecture. The model is fit with observed-calculated gravity and magnetic, showing thinned continental crust underlies the Makassar Straits.

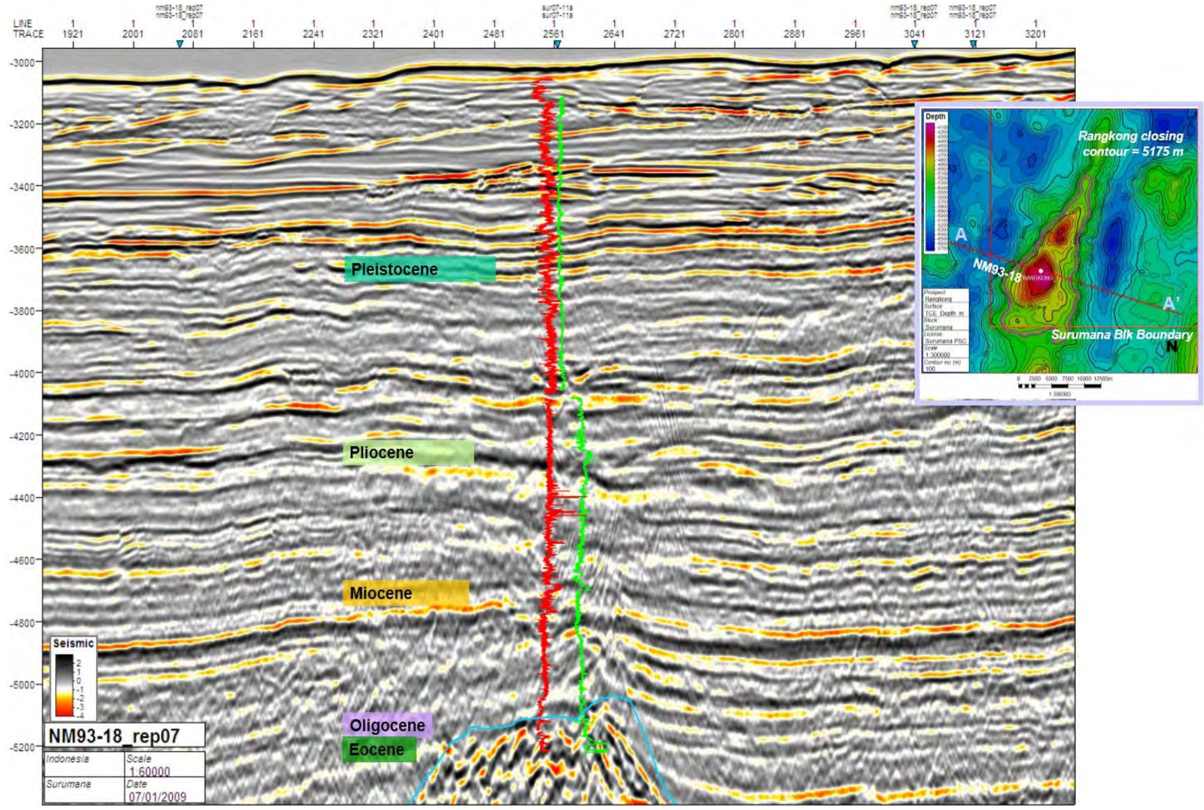


Figure 4 - Post-drill Rangkong-1 time section. The well was drilled by ExxonMobil Surumana in 2011. The well found very thin Oligocene carbonate cap on Eocene volcanic. No hydrocarbon was discovered.

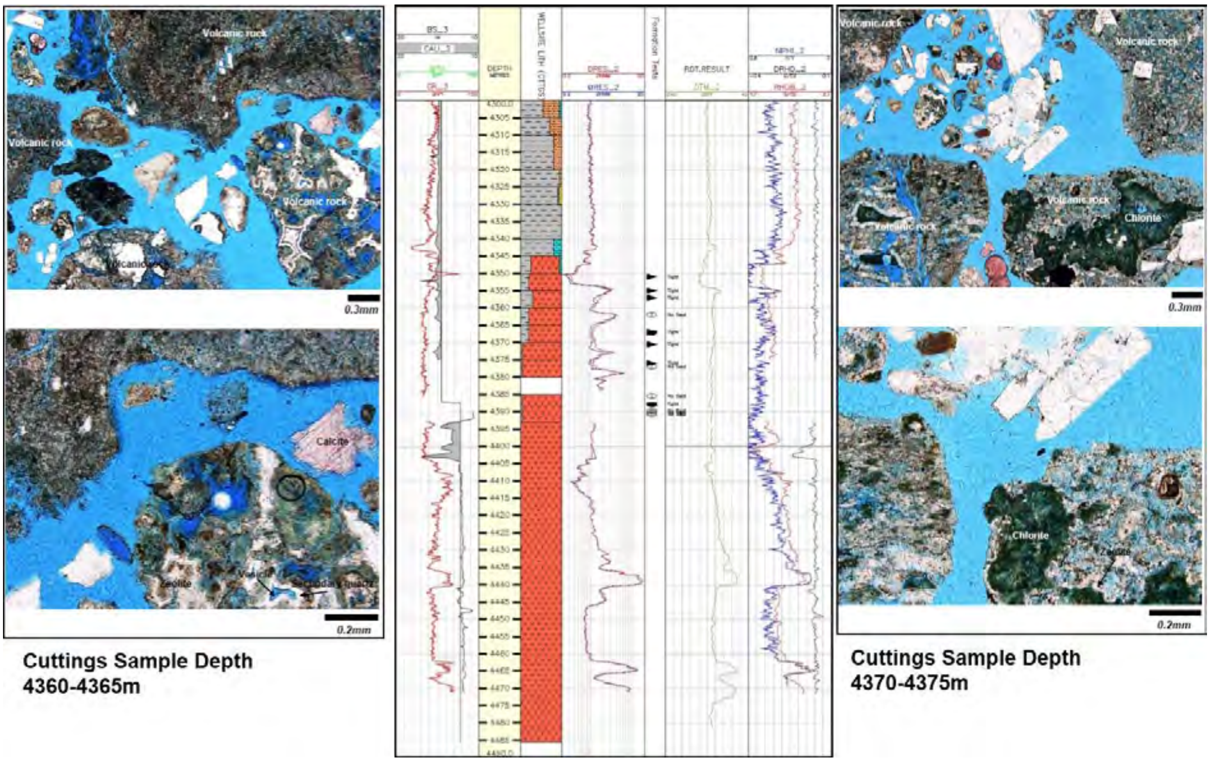


Figure 5 - Rangkong-1, Surumana, post-drill basement cutting and thin sections description. The cuttings are altered rock. The basement cuttings are volcanic basaltic igneous rocks that have porphyritic texture, in the cuttings there also abundant of glass. They show medium plagioclase as phenocryst, microlites of plagioclase and glass as groundmass. The glass occupies interspaces between microlites of plagioclase (feldspar) in haphazard orientation, a typical in many lavas. Zircon is encountered on thin sections.

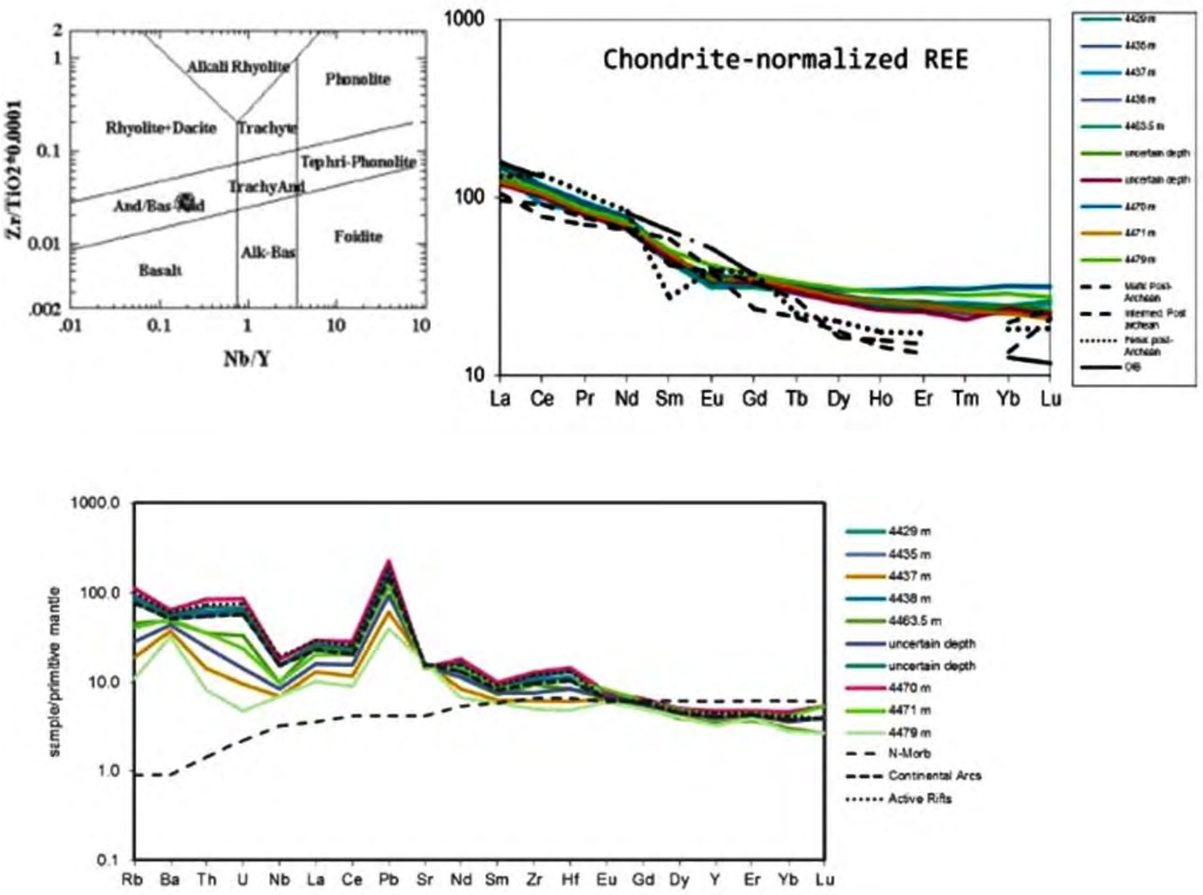


Figure 6 - A. By comparison to major elements (which are often quite soluble), the trace elemental ratios suggest a much more consistent andesite composition. B. Compositionally, the Rangkong volcanic rocks could be continental arc rocks or rift related volcanic. Both are similar in that they potentially mix primitive sources with evolved crustal material. Seems consistent with tectonic history of the region. C. Relatively low degree (~8-10%) of partial melt of primitive sources, or potential crustal contamination, consistent with arc.

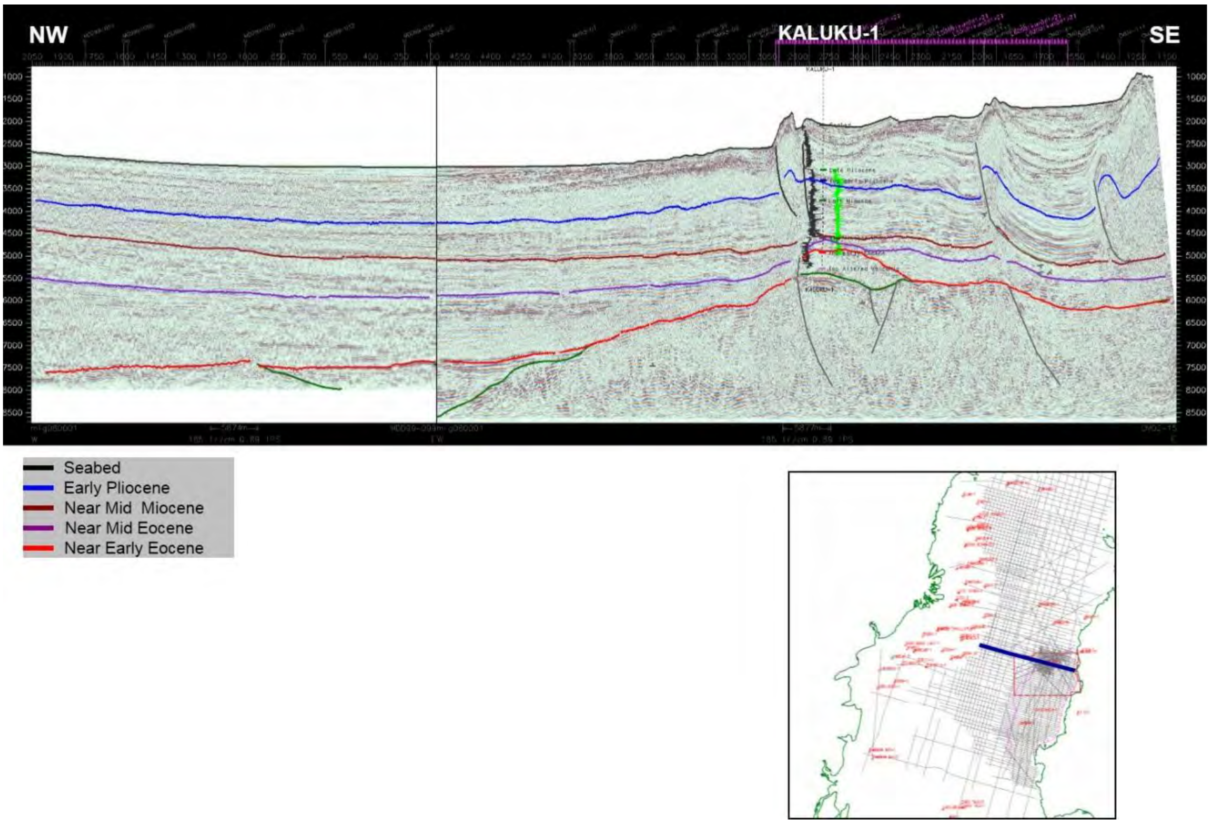


Figure 7 - Seismic section across the location of Kaluku-1 well. There is tectonic barrier between Paleogene and Neogene sections. The Paleogene sections are rifted in extensional deformation. The Neogene sections are compressive forming fold-thrust belt in thin skinned-tectonic deformation. The Kaluku-1 well discovered oil from the Eocene section.

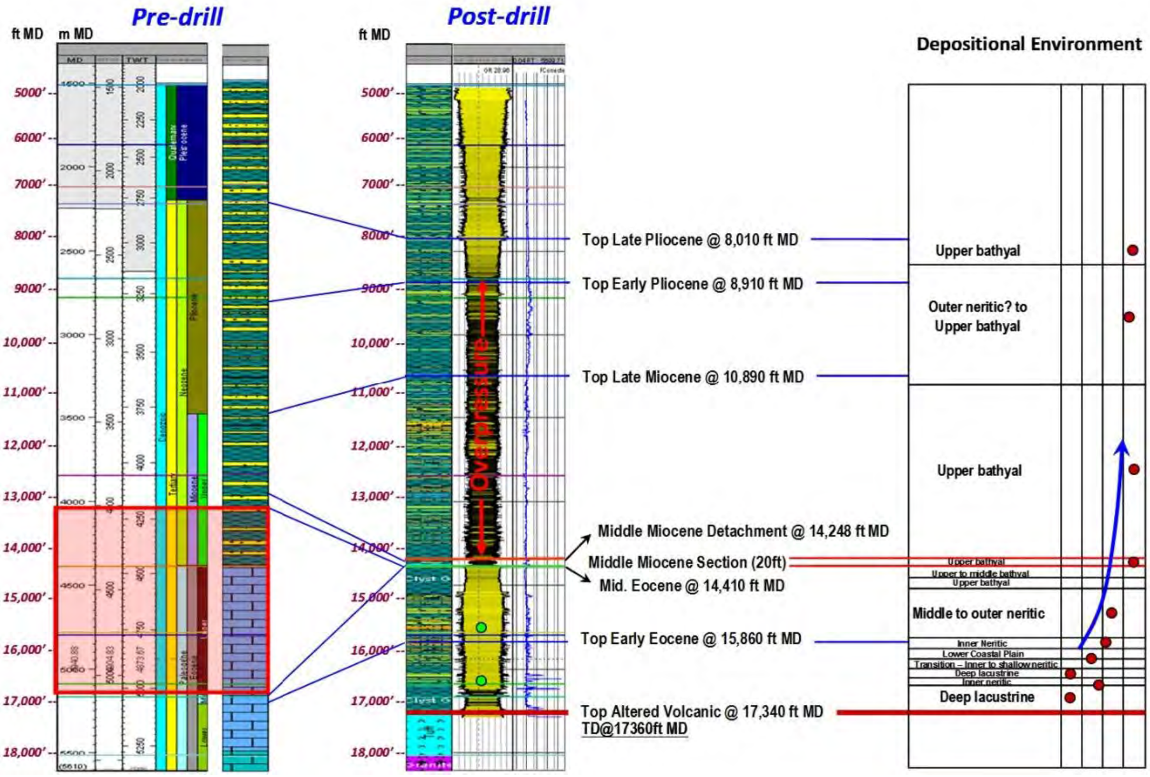


Figure 8 - Pre-drill vs. post-drill stratigraphic interpretation of Kaluku-1 well and its depositional environment based on biostratigraphic analysis. The carbonate objective is not present. The well was deepened into the Eocene section and encountered two sandstone intervals with oils.

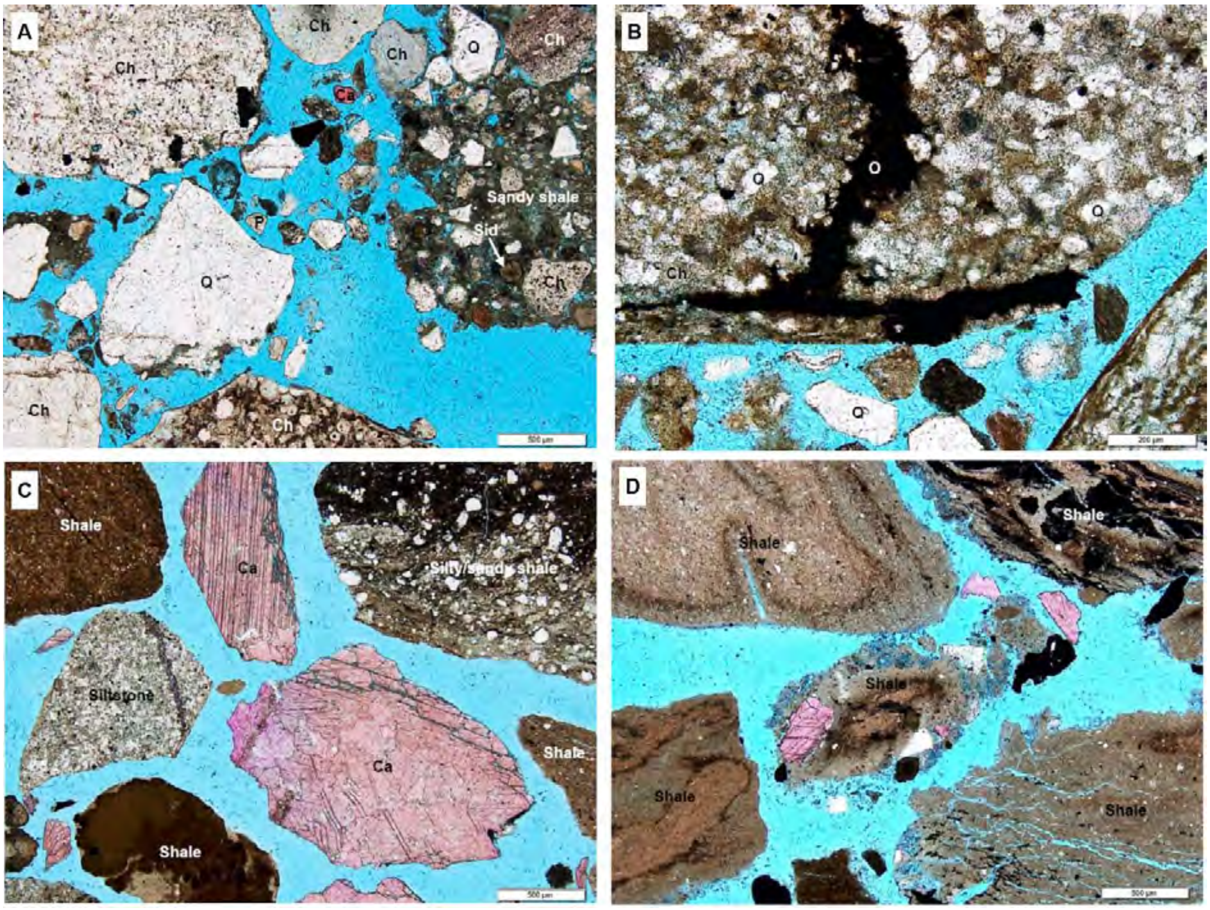
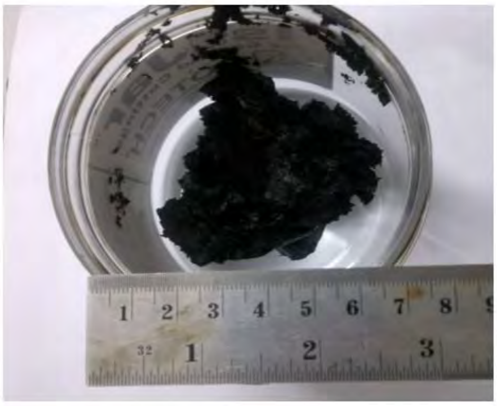


Figure 9 - A. Cuttings at 15,760 ft Kaluku-1 composed of loose grains, shale, calcareous sandstone, and recrystallized limestone, Eocene. B. 16,760 ft Kaluku-1 similar composition, Eocene. C. 17,210 ft, volcanic basement composed of shale, loose grains, recrystallized limestone. D. 17,350 ft, volcanic basement. Shale on cuttings are products of diagenetic change of volcanic. Ca-calcite, Q-quartz, Py-pyrite, Sid-siderite, Ch-chert, O-organic material.

OIL 15,572’



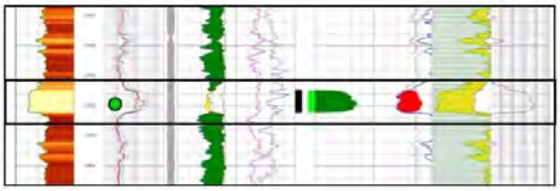
OIL 16,702’

Depth	Colour	Crude Oil Composition					Carbon Isotop Data				Maturity Parameter	Bulk Properties		
		Sat	Aro	NSO	Asph	Sat/Aro	δ^{13}C Sat. ‰	δ^{13}C Aro. ‰	δ^{13}C Whole Oil ‰	Cv	Rc (Aromatic)	Bulk (API)	Wax (% Wt)	Sulphur (% Wt)
15752	Black	70.47	14.57	2.95	12.01	4.84	-23.93	-19.25	-18.47	6.16	0.57	25.5	21.09	0.06
16702	Black	79.74	10.85	2.71	6.7	7.35	-20.25	-20.1	-18.45	-5.04	0.67	?	?	?

Kaluku-1 Postdrill

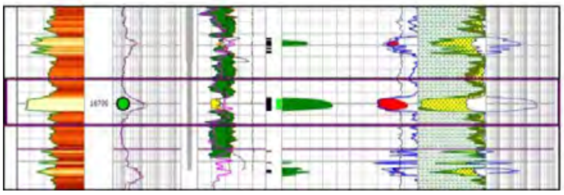
Mid Eocene Limestone (14893-14920’)

- Mudstone to Wackestone, Packstone in part, Argillaceous
- Potential pay: 20 ft
- Porosity (average) 28%
- Permeabilities 100-200 mD
- Sw 50-60%



Middle Eocene Sandstone (15733-15753’)

- Potential pay: 17 ft
- Porosity (average) 30%
- Permeabilities 450 mD
- Sw 30-40%



Early Eocene Sandstone (16694-16706’)

- Potential pay: 9 ft
- Porosity (average) 30%
- Permeabilities 500 mD
- Sw 30%

Figure 10 - Above. Oil samples from two depth interval within Eocene sections discovered by Kaluku-1 well. The oils are very waxy, solidified at surface. Table shows geochemical characteristics for the two oils. The oils were sourced by shallow lacustrine facies with some terrestrial inputs. Below. The reservoir characteristics of two sandstone intervals containing oils. The quality of sandstones are very good to excellent.

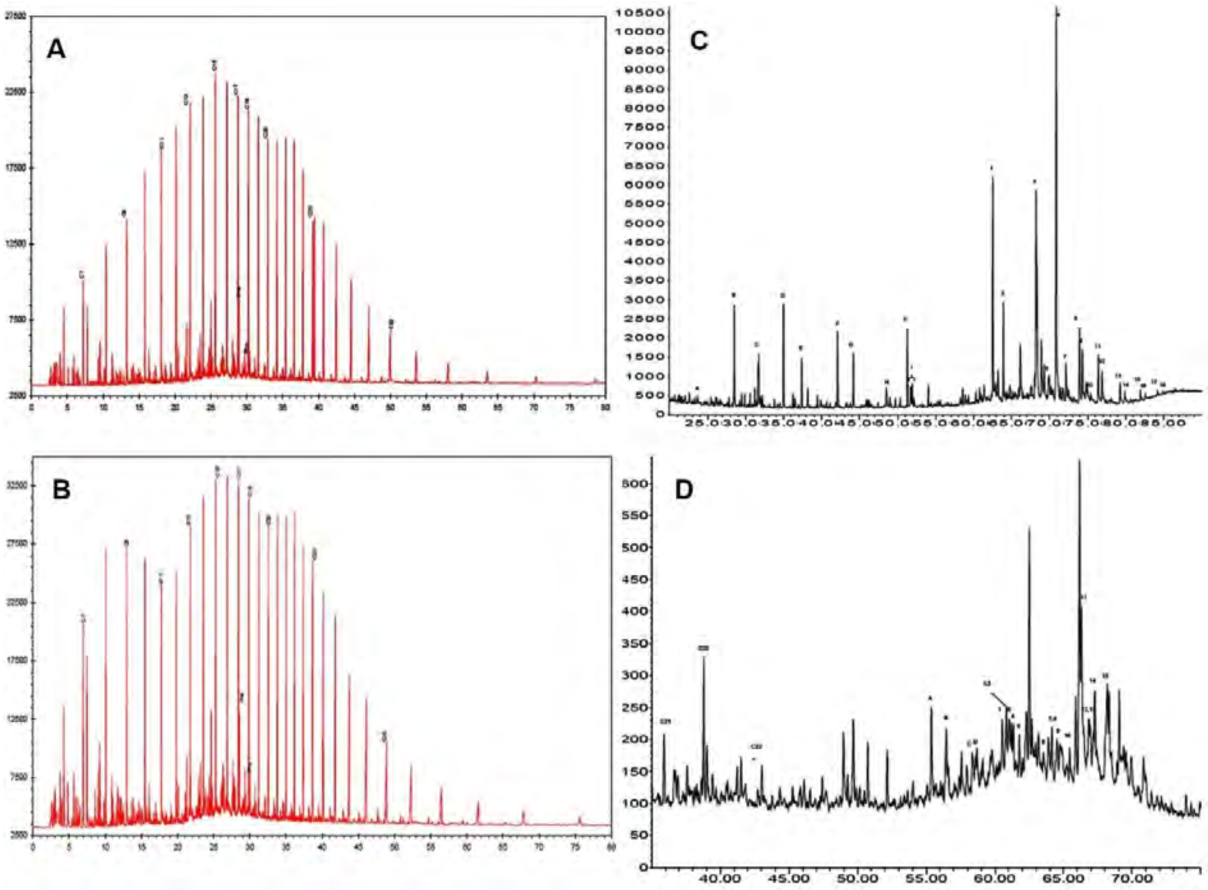


Figure 11 - A. C5+ whole oil gas chromatography of Kaluku-1 oil sample at 15,752 ft, pr/ph 2.48. B. C5+ whole oil gas chromatography of Kaluku-1 oil sample at 16,702 ft, pr/ph 2.25. The two gas chromatography shows high abundance of saturates. The high levels of normal alkanes indicate that these oils were sourced from aquatic sub-oxic sediments, combined with very low sulfur content (< 0.1 %) and moderate wax content, is obvious it is fresh water aquatic or shallow lacustrine. C. Biomarker m/z 191 triterpane of oil at 15,572 ft Kaluku-1 oil, shows Eocene shales source from shallow lacustrine. Shales is shown by low norhopane/hopane ratio, nonmarine is shown by reducing extended hopane, lacustrine is shown by high tricyclic terpane, low peak of oleanane due to lacustrine environment and Eocene. D. Biomarker m/z 217 sterane of oil at 15,572 ft Kaluku-1 oil shows a nonmarine oil with high C29 sterane and numerous bicadinane.

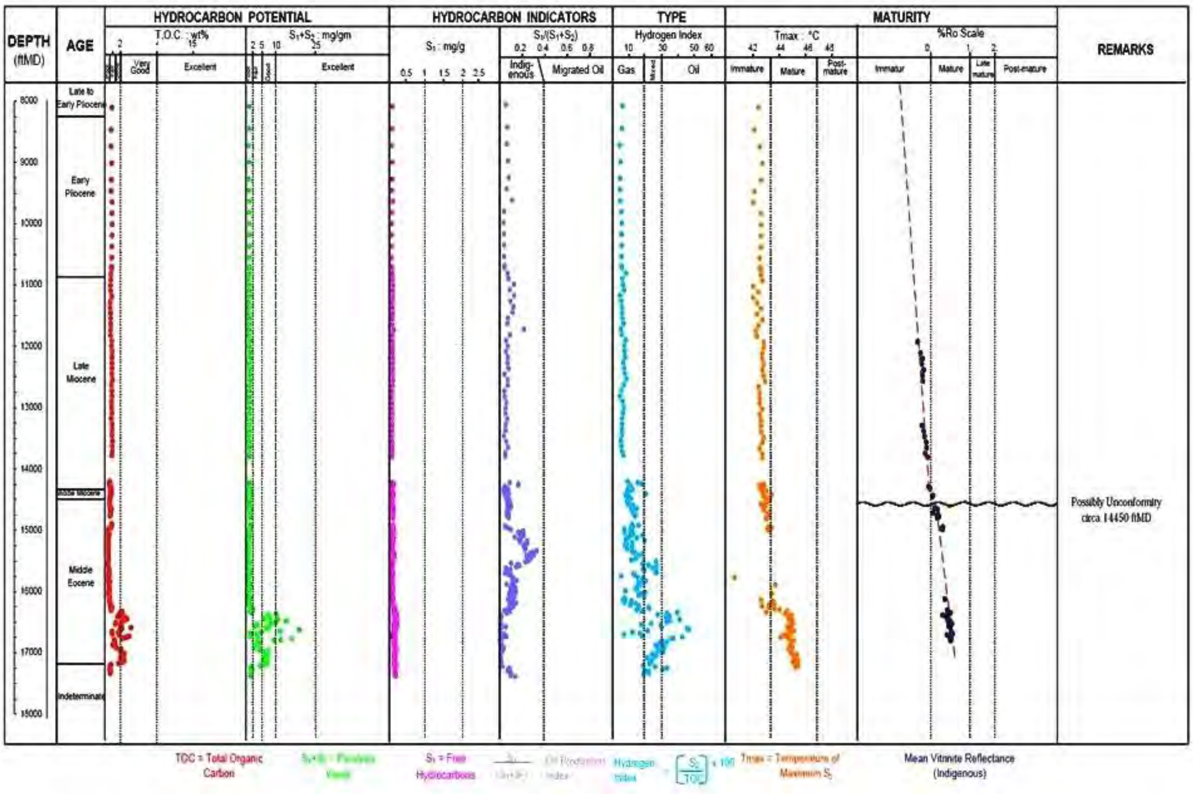


Figure 12 - Geochemical log of Kaluku-1 well, showing source potential, hydrocarbon proneness and occurrences, and source maturity. Intervals of lower part of Middle Eocene to Early Eocene are the best with rich source potential, hydrocarbon indications, and mature.

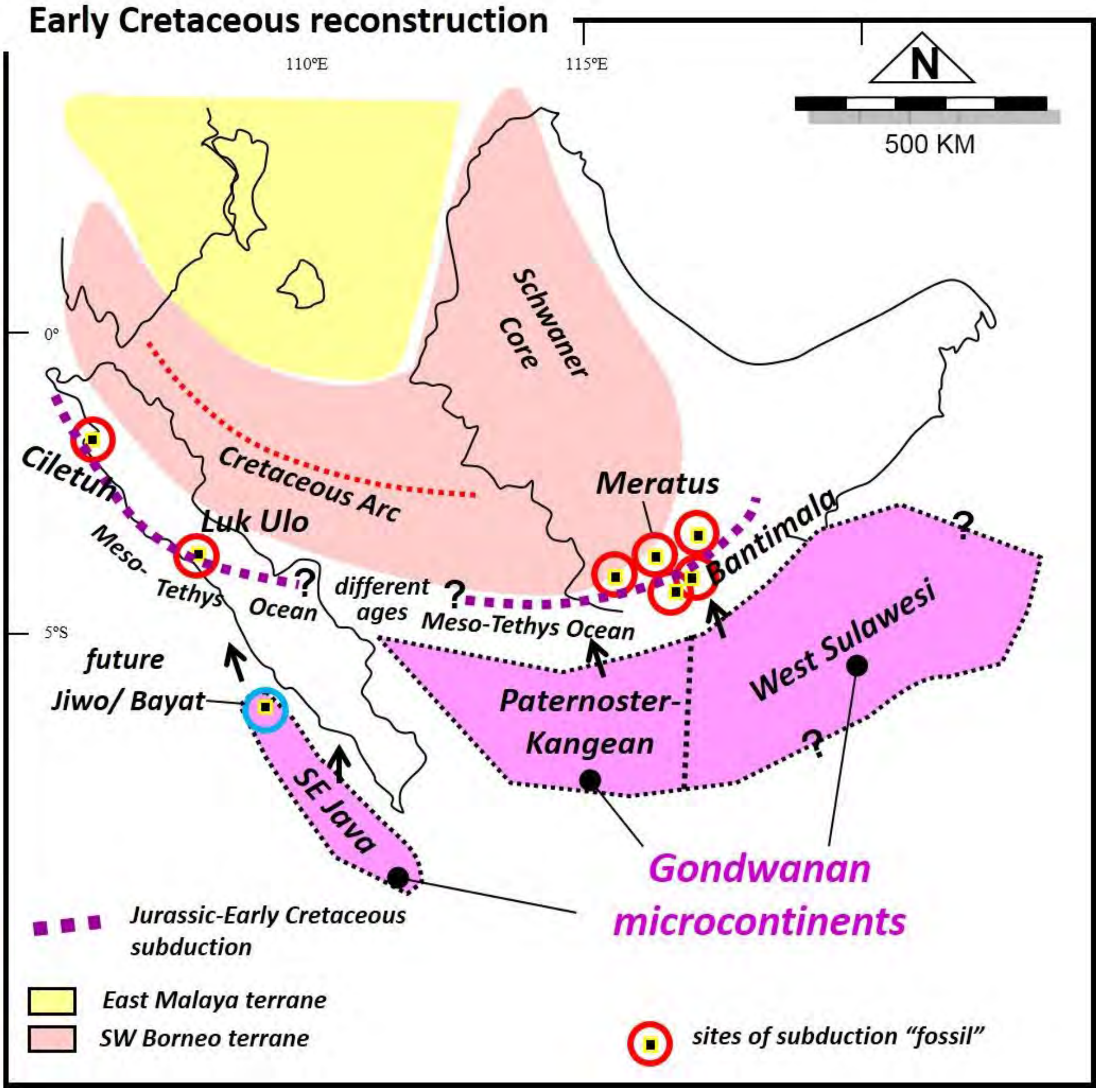


Figure 13 - New tectonic reconstruction of SE Sundaland as proposed by Satyana (2014). The site of later Makassar Straits is occupied by microcontinents from Gondwana. The microcontinents are called Paternoster-Kangean and West Sulawesi. Zircon occurrences in Rangkong-1 and Kaluku-1 basement and Sm/Nd dating of Rangkong-1 show contribution from Proterozoic age (1300-1600 Ma) support that the deep basement of the Makassar Straits is Gondwanan microcontinent.

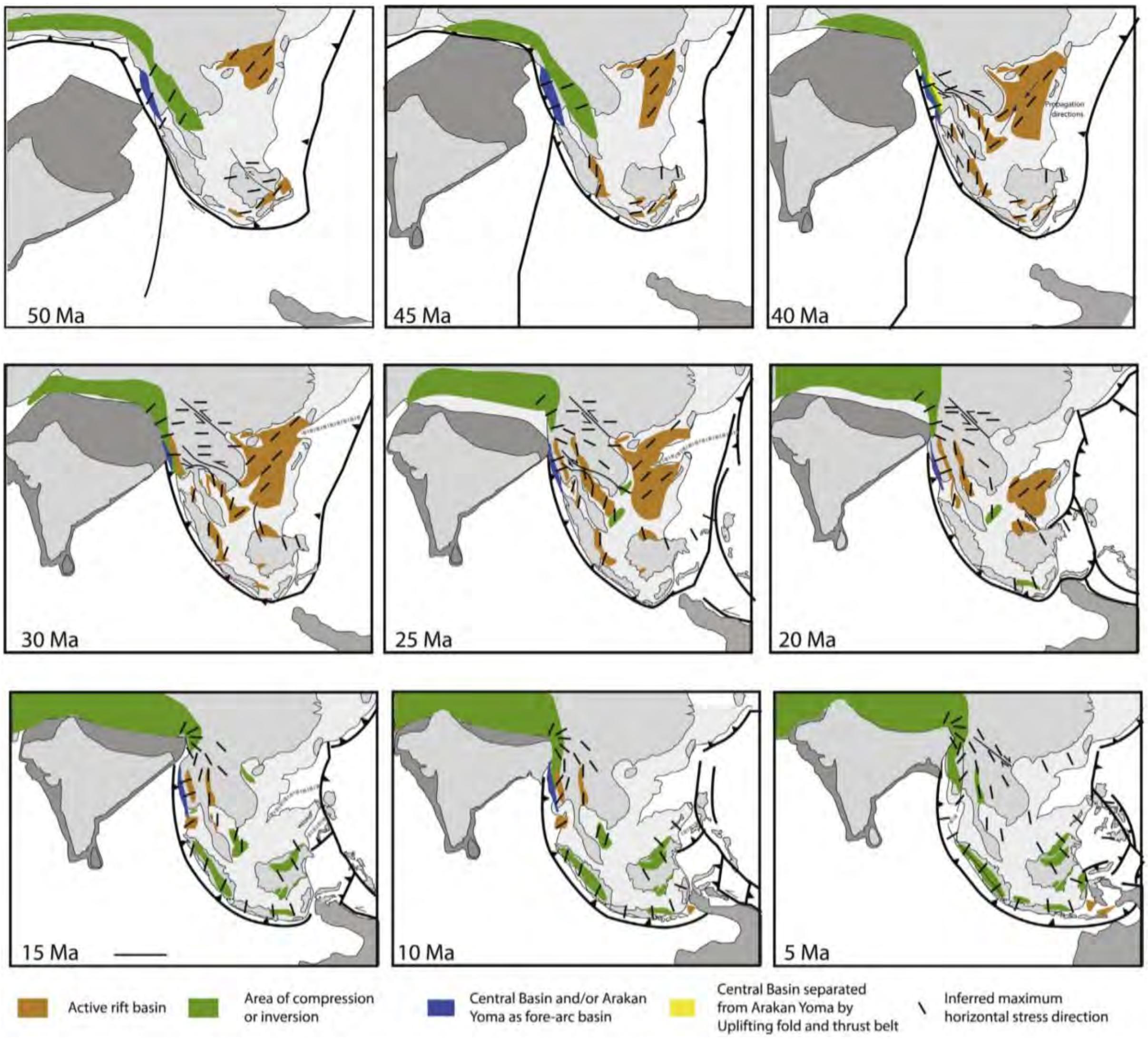


Figure 14 - Series of reconstructions showing the geometries of the Sunda Trench bordering most of Sundaland, with respect to the main neighboring continental masses. The cartoon highlights the timing of opening (orange colour) and shortening (green colour) of basins in relation with the respective locations of India and Australia during the Tertiary (after Pubellier and Morley, 2013).

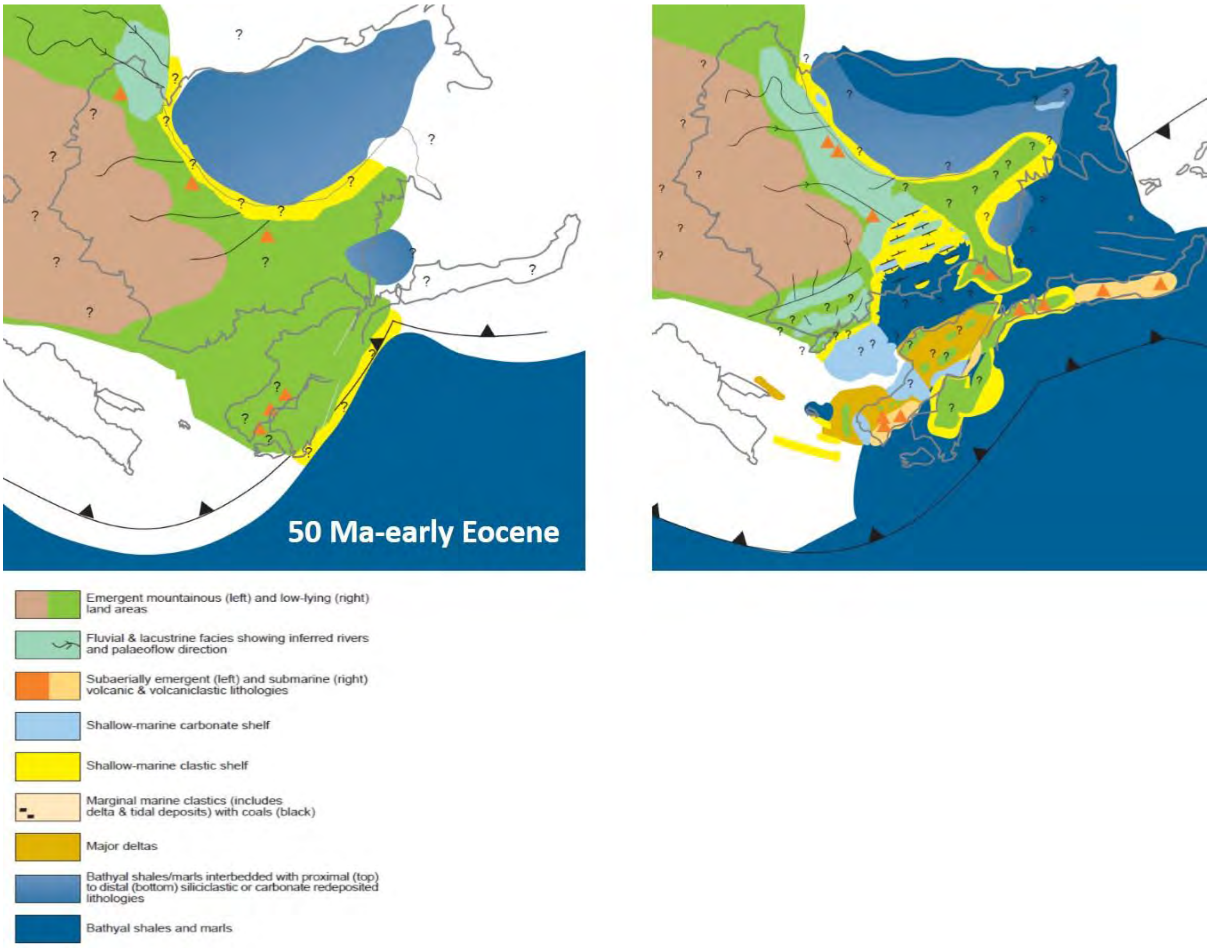


Figure 15 - Paleogeographic setting of Kalimantan and Sulawesi during Early-Middle Eocene in the period of rifting of the Makassar Straits. The opening of the Makassar Straits was resulted from backarc rifting due to subduction rollback related to slower rate of subduction because far field stress of India approached Eurasia. Note the presence of major delta facies in West Sulawesi, it possibly contributed sands and shales for Kaluku discovery (after Wilson and Moss, 1999).

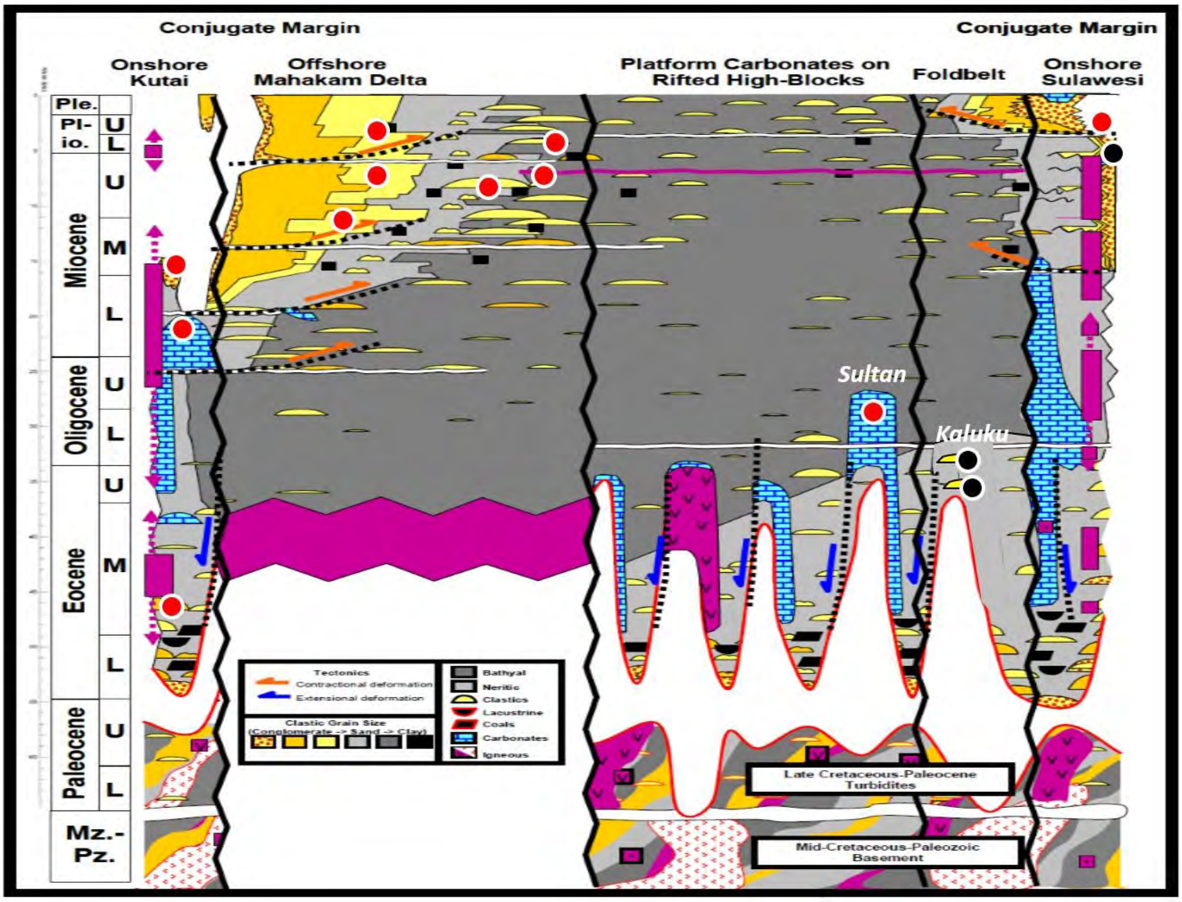


Figure 16 - North Makassar chronostratigraphic section and petroleum occurrences and plays from Kutai Basin, western and eastern parts of the Makassar Straits, and western Sulawesi. Petroleum in Mahakam Delta and its deepwater facies are very prolific, all in Miocene and Pliocene section. Play type of Eocene section is proven only in West Sulawesi Offshore on rifted basement where Kaluku discovery occurs at the horst block, the active sources are within grabens. Gas discovery on reef above the horst block is from Sultan, but mostly biogenic origin. In onshore Sulawesi, numerous oil and gas seeps occur due to faulting on Neogene to Pleistocene sections (modified after Bacheller III).

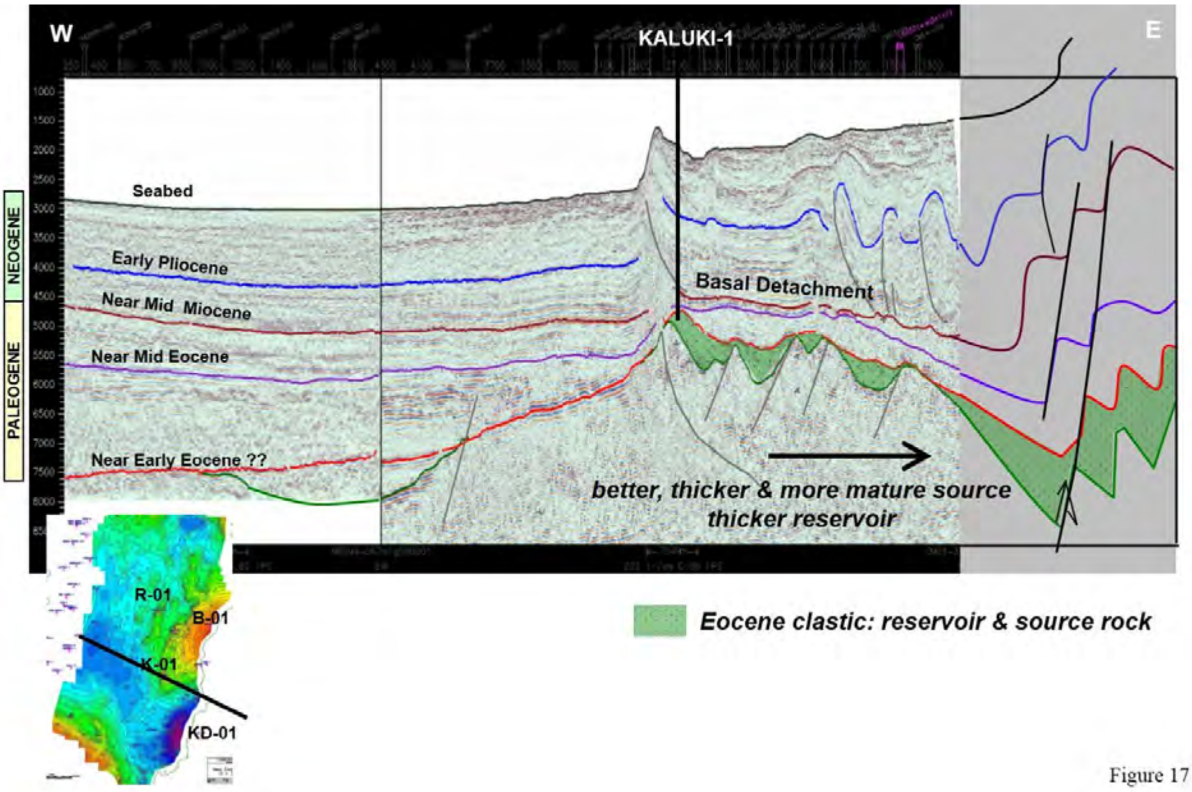


Figure 17

Figure 17 - Seismic section across the Kaluku discovery, continued by schematic section on transition area to onshore Sulawesi. Based on Kaluku-1 discovery, further exploration should target the area to the east of Kaluku discovery until transition zone with onshore Sulawesi. Here the source rocks are considered to be thicker, better quality, earlier maturation hence generating more oils (more volume). The sandstone reservoirs will also be thicker. New 2D high resolution or 3D seismic data will be required for better evaluation.