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THE EMERGENCE OF PRE-CENOZOIC PETROLEUM SYSTEM IN EAST JAVA BASIN: CONSTRAINTS FROM NEW DATA AND INTERPRETATION OF TECTONIC RECONSTRUCTION, DEEP SEISMIC, AND GEOCHEMISTRY

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ABSTRACT

The Cenozoic East Java Basin is aprolific petroleum basin in Western Indonesia. It has been explored and producing for 125 years Cenozoic. The proven source rocks are carbonaceous shales of middle Eocene fluvio-deltaic to marginal marine Ngimbang Formation, feeding various intervals of reservoirs from pre-Eocene to Pleistocene ages. The processes of petroleum generation-migration-charging, stratigraphic-structural trapping, and preservation of accumulation occurred in the Paleogene and Neogene.

New tectonic reconstructions argue that various Australian-derived microcontinents collided with SE and East Sundaland during mid-Cretaceous times. This argument is supported by deep seismic sections in offshore areas of South Makassar, East Java Sea, and South East Java Forearc, which show a considerable pre-Cenozoic sedimentary section of probable Mesozoic and Paleozoic age. In addition, comparison between bulk properties, biomarkers and isotopes of Sepanjang oils and general East Java oils; lead to a conclusion that there is another proven source rock which has actively generated oils since the Miocene, namely Lower Cretaceous marine shales, charging the Sepanjang field in the Kangean area.

This impliesan emergence of Pre-CenozoicCenozoic petroleum system in East Java Basin and its surrounding areas. Therefore, the Mesozoic and Paleozoic sections of the microcontinents may contain important source rocks, reservoirs, seals, and overburdens, as shown by their counterparts in NW Shelf of Australia from where these microcontinents are proposed to have originated. Trap formation, in addition to the generation, migration and preservation of petroleum from the pre-CenozoicCenozoic source rocks, is thought to have occurred sequentially during the Cenozoic following tectonic episodes in the East Java Basin.

The presence of actively-generating Lower Cretaceous source rocks within the pre-Cenozoic section of the East Java Basin – in addition to other basins underlain by Australian-derived fragments - warrants further exploration. CenozoicCenozoic

INTRODUCTION

The East Java Basin is one of the first basins in Indonesia to be explored. It has received more than 140 years of exploration since the 1800's, and has been producing oil and gas for 125 years.

The East Java Basin is known by most workers and researchers to be CenozoicCenozoic hydrocarbon basin with proven source rocks derived from the Late Eocene to Early Oligocene syn-rift Ngimbang Formation (Satyana and Purwaningsih, 2003, and Doust and Nobel, 2008). This understanding has resulted in historic and current exploration to be focused on the Cenozoic section only.

However, deep seismic data of Kangean to South Makassar offshore areas (Emmet et al., 2009) and the East Java forearc basin (Deighton et al., 2011) (Figures 1, 4-8), recent tectonic reconstructions of Southeast and Eastern Sundaland (Hall, 2012; Satyana, 2014a, 2014b) (Figures 2-3), new geochemical data from an oil field in Kangean area (Sutanto et al., 2015; Musu and Sutanto, 2015; Sutanto et al., 2016) (Figures 9-16), and new biostratigraphic data of an exploration well in Kangean area, all lead to the consideration that in some parts of the East Java Basin there are Mesozoic source rocks which have been generating oils since the Miocene and trapped within an Eocene reservoir in the Kangean area..

This opens the new opportunity of exploring Mesozoic targets (source, reservoir, trap) or charging possibility to Paleogene reservoirs in the East Java Basin. The new identified targets are beyond the classic targets so far explored in the East Java Basin and will therefore, enrich the basin's prospectivity.

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This paper will summarize the emergence of the new petroleum system (Figure 19), with Pre-Cenozoic targets (Figures 17-18), in the East Java Basin and its surrounding areas, based on various new data and recent studies, including: deep seismic, geochemistry, and tectonics.

DATA & METHODS

Published and previously unpublished geological, geophysical, and geochemical data, both old and new,, are the main inputs of this study. In particular, recent deep seismic data, and recent geochemical analyses of East Java Basin have been examined, reviewed and synthesised to give an integrated evaluation on the possibility and potential of Mesozoic source rocks in the East Java Basin.

RESULTS & DISCUSSIONS

Cenozoic Petroleum System of East Java Basin

Most workers know, and publications show, that the East Java Basin has been prolific for more than one hundred years, with the elements and processes of the active petroleum system developing during the Cenozoic. The Proven, and significant source rocks are Eocene Ngimbang coaly shales. Oils and gases derived from these shales entered into numerous reservoirs distributed acrossEocene to Pleistocene levels, but with the most significant reservoirs located within the Early Miocene Kujung reefs, Middle Miocene Ngrayong sandstones, and Late Miocene Wonocolo sandstones.

Regional geochemical studies of East Java oils and gases (Satyana and Purwaningsih, 2003) show that the East Java oils are typically waxy, indicating that they were derived from non-marine source rocks. All of the oils thus far identified contain properties associated with terrestrially derived kerogen. They analyzed 86 oil samples (49 from onshore and 37 from offshore) from theEast Java Basin and showed that the onshore oil samples have API (density of oil) ranging from 8° to 69° with an average of 29°, and sulfur ranging from 0.02 to 0.68 wt.%, with an average of 0.19 wt.%. Offshore oil samples show API ranging from 10-58° with average of 36°, and sulfur ranging from 0.01 to 0.70 wt.%, with an average of 0.24 wt.%. These numbers show that the hydrocarbons were generally derived from non-marine sources. It is also in line with the cross plot of pristane (pr)/ n-C_{17} to phytane(py)/ n-C_{18} which shows that the hydrocarbons were derived from humic kerogen (peat-swamp). The dominant peaks of Pr and Ph also indicate that hydrocarbons derived from sources are fluvio-deltaic. Moreover, the ternary diagram of m/z 217 sterane C_{27}-C_{28}-C_{29} also showed that the hydrocarbons were derived from sources that have a contribution of terrestrial organic material. The most probable sources for the oils are non-marine to marginal marine shales and coals of the Middle-Late Eocene Ngimbang Formation.

Three genetic types of natural gases can be distinguished in the East Java Basin (Satyana and Purwaningsih, 2003): (1) thermogenic gases which are either associated or non-associated with oils produced predominantly from Miocene and older reservoirs, (2) bacterial/bacteriogenic/biogenic gases which are found predominantly in the Pliocene-Pleistocene reservoirs, and (3) mixed gases of thermo-biogenic origin which are predominantly present in reservoirs of Late Miocene age, but are also found in older and younger reservoirs.

Five petroleum systems were proposed by Howes and Tisnawijaya (1995) and updated by Doust and Noble (2008). These are as follows:

1. Ngimbang–OK Ngrayong (.) PS in the Cepu area of East Java;

2. Ngimbang–Ngimbang (!) PS in the Kangean area offshore area north of Bali;

3. Ngimbang–Kujung (!) PS in the Cepu and Madura basins;

4. Tertiary–Miocene (.) PS in the Muriah Basin—this is largely a biogenic gas system; and

5. Tertiary–Pliocene (!) PS in the southeast Madura and north Bali areas, a biogenic gas system.

Up to now, all ventures of exploration in the East Java Basin base their evaluations on the existing and proven Cenozoic petroleum system.

However, in the last five years, deep seismic data, updated tectonic reconstructions based on new data, and new geochemical analyses of oils and rock samples, all indicate the presence of active Mesozoic source rocks underlying the Cenozoic East Java Basin. It is therefore possible that many of the Cenozoic reservoirs have been fed by pre-Cenozoic sourcees.

A new tectonic reconstruction of Southeast and East Sundaland, along with deep seismic data showing the presence of likely Mesozoic horizons, and new geochemical oil analyses showing contrasting anomalies to those previously described for East Java oils, are presented and discussed here, and enable the new Mesozic petroleum system to be addressed.

Mid-Cretaceous Collision of Microcontinents to Southeast and East Sundaland

Detailed discussions on the proposed new tectonic reconstruction of Southeast and East Sundaland during the Mesozoic, in the area where the East Java Basin later developed can be found in Satyana (2014a, 2014b, 2015). The most important aspect of this reconstruction in terms of the petroleum geology of the East Java Basin and surrounding areas, is the presence of Australia/Gondwana-derived microcontinents and sedimentary cover, which collided against the margin of Southeast and East Sundaland during the mid-Cretaceous (Figure 2).

Southeast and East Sundaland, presently located between the Makassar Straits, Western Sulawesi, Kangean, and East Java areas, are proposed to comprise various microcontinents, which have been named, and interpreted in different ways by different people. The names include: Paternoster, Paternoster-Kangean (including West and South Sulawesi), Bawean, East Java , East Java-Makassar Straits, Argoland, and SE Java microcontinents (references for these microcontinents can be found in Satyana, 2015)). As for the East Java Basin, Bransden and Matthews (1992) were the first to propose a unique East Java 'microplate' on the basis of pre-Cenozoic sedimentary sections.

These microcontinents form the basement of the Makassar Straits as interpreted fromNd geochemistry of Rangkong-1 (Exxon Surumana, 2009) which penetrated volcanic 'basement' of the North Makassar Straits. The geochemistry suggested a mixture of primitive (mantle) magmas and Proterozoic continental sources of ~1300-1600 Ma in ages (Satyana, 2015). 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.

Collision of the microcontinents against the Sundaland margin is interpreted to have taken place in the mid-Cretaceous time, at around 100 Ma. The Meratus suture is a remnant of this collision. Outboard of the Meratus suture, East Java and West Sulawesi are underlain in part by Archean continental crust. Geochemistryand zircon dating (Smyth 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).

As noted by Hall. (2009), the mid Cretaceous collision of continental fragments (at around 112-90 Ma – Figure 3) 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 He goes on to highlight that 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 (Hall, 2009).

Derivation of the microcontinents from NW Australia opens the possibility for Mesozoic sections deposited in rifted structures formed within the microcontinents. The equivalent sections in the present-day NW Shelf of Australia are very prolific as petroleum sources and reservoirs, as testified by the many oil and gas fields which have been discovered in Mesozoic sections.. The presence of similar Mesozoic sections in the microcontinents which collided against Southeast and East Sundaland potentially provide a similar opportunity for petroleum prospectivity in Mesozoic targets of East Java, South Makassar, and East Java forearc areas.

Deep Seismic Data Showing the Presences of Pre-Cenozoic Sections Overlying the Microcontinents

East Java Sea and South Makassar Straits

In early 2000, ION-GXT started acquiring a number of regional 2-D seismic reconnaissance surveys

("SPAN" surveys) to image the deep crustal structure of basins and continental margins interesting to the petroleum industry (Granath et al., 2009) (Figure 4). Acquisition of "JavaSPAN™" was completed in early 2008 in the Java Sea back-arc region from central Java to Tukang Besi in the south, and extending northward between Kalimantan and Sulawesi in the Makassar Straits (Granath et al., 2009) . The survey was comprised of 9800 line/km of 2D data (Dinkelman et al., 2008, in Granath et al., 2011). Acquisition parameters included a 25 m shot interval, 12.5 m group interval and maximum offset of 9,000 m. The record length is 18 seconds and the data were processed to pre-stack time images of 16 seconds and pre-stack depth images of 40 km record length (Granath et al., 2011).

These data, presented by Granath et al. (2009), provided pre-stack depth images to 40 km, and allowed them to make new interpretations of the basement structure and its influence on the overlying sedimentary cover. In the East Java Sea, the new seismic data revealed thicker intervals of pre-Cenozoic sedimentary rocks than had previously been thought to exist below the normally accepted acoustic basement (Granath et al., 2009).

Their survey imaged stratigraphic thicknesses of up to 5 km of pre-Middle Eocene strata locally preserved in faulted synclines 20-50 km wide below the strong regional angular unconformity (Emmet et al., 2009) (Figures 5, 6). These "synformal keels" (Emmet et al., 2009) were reported to lie below the known inversion structures, indicating the Eocene extensional basins and Miocene inversions nucleated on the pre-existing structures (Emmet et al., 2009). Emmet et al. (2009) recognized a possible Australian provenance of the keel strata. The results of the survey thus support the inference that the East Java Sea is underlain by a composite of continental basement blocks or terranes believed to have been rifted from Australia in the Jurassic and accreted against an arc on the SW flank of Kalimantan in the mid-Cretaceous (Emmet et al., 2009). All commercial hydrocarbon plays and production have been limited to the younger sequences above the base Middle Eocene unconformity, yet a substantial section lies below that unconformity, as demonstrated by Granath et al. (2009). The younger and less-deeply buried strata in cores of synclines may be unmetamorphosed and may source pre-Cenozoic hydrocarbon systems.

Based on the deep seismic surveys in JavaSPAN program, Granath et al. (2010) summarized that the pre-Cenozoic basement and overlying supracrustal section in the East Java Sea has been imaged systematically for the first time. These new data substantiate the pre-Cenozoic history involving a long period of sedimentation and deformation similar to the Australian Arafura and NW Shelf. It rifted from the Australian craton and collided with Sundaland prior to the well-known Eocene extensional tectonics of the area. The fact that much of the pre-Cenozoic section may be preserved led Granath et al. (2010) to suggest that unknown hydrocarbon system(s) may be present below known production levels.

South East Java Forearc, North Indian Ocean

In 2009 TGS conducted a reconnaissance 2D seismic survey (SJR-09) into the deeper South Java Basin with the aim of providing deep imaging of this poorly known area (Deighton et al., 2011) (Figure 7). The SJR-09 survey revealed a thick (3.5 seconds TWT) stratigraphic section of parallel bedded sediments beneath the central Java forearc basin buried under 2+ seconds TWT of midlate Cenozoic forearc fill that Deighton et al. (2011) suggest bear similarities to Mesozoic or Paleozoic NW Shelf of Australia sections in present orientation (relatively un-faulted in N-S sections and block faulted in E-W sections).

Their assessment of publically available regional interpretations from Geoscience Australia which compare fairly random Mesozoic and/or Paleozoic sections from the NW Shelf highlighted that while there are some differences in brightness of various packages (perhaps reflecting more volcanics), the thickness of megasequences and general fault style and spacing are very similar (Deighton et al., 2011).

Subsequent infill surveys acquired in 2010, including gravity data, have provided a grid of about 20-25km spacing (Figure 7) and define the along-arc distribution of the probable Mesozoic section which seems to be restricted to the area between the deeper Southwest Java and Lombok Basins, both of which are suggested as probably underlain by crust of ophiolitic and/or island arc affinity (Deighton et al., 2011).

Deighton et al. (2011) characterized the seismic character of the considered Mesozoic sections which show asediment column of over 3.5 seconds TWT thickness below the OFB (Outer Forearc Basin) and FS (Forearc Slope). They postulate this to be of possible Mesozoic age, but definitely pre-Oligocene (Figure 8). The upper section is represented by a highly faulted and folded geometry, which appears to be more intense to the west of their study area below the OFB. They also note that the amplitude response of the upper section is mixed; reflectors are typically poor continuity and sub-parallel. Furthermore, the pervasive faulting obscures the large-scale depositional architecture. They suggest that this section may be tentatively interpreted as alluvial to delta plain; with the higher amplitude sub-parallel facies being sand-prone e.g. channel, and the lower amplitude areas being floodplain claystones/shales. They show lower section as much more gently faulted and folded throughout their study area when compared to the upper section. The continuity of the reflectors in this section is also better than the upper section, which they suggest may be a result of the less intense faulting and folding. In general the lower section has a lower frequency and higher amplitude seismic response when compared to the upper section.

Deighton et al. (2011) go on to suggest slight facies changes in the lower section from west to east: from higher amplitudes, good continuity, parallel reflectors indicating mixed clastic and carbonate sediments, possibly tidal carbonates and shoreline sandstones; to slightly lower amplitudes, with moderate continuity, parallel to sub-parallel reflectors, that they tentatively interpret to record a more transitional facies, e.g. shoreline to coastal plain. They also infer thepattern of decreasing amplitudes and continuity observed from west to east, may also be recording a transition from shoreline to coastal plain facies.

Infill seismic in the offshore southeast Java Basin presented by Deighton et al. (2011) confirmed the presence of a thick sedimentary section, interpreted as Mesozoic, continental crust. If source rocks are present in these sediments, the higher thermal gradient resulting from continental crust should improve the hydrocarbon prospectivity of the forearc basin south of east Java (Deighton et al., 2011).

Geochemical Anomaly of Sepanjang Oils

East Java oils are typically waxy, indicating that they were derived from non-marine source rocks (Satyana and Purwaningsih, 2003). The dominant peaks of prystane and phytane, mostly > 4.0 also indicate that the hydrocarbons were derived from fluvio-deltaic source rocks.. Moreover, the ternary diagram of m/z 217 sterane C_{27}-C_{28}-C_{29} also showed that the hydrocarbons derived from sources with a predominant terrestrial organic origin. Oleanane index of the oils > 0.20, mostly between 0.5-0.8, show that the source rocks were Cenozoic and fluvio-deltaic facies.

As previously mentioned, Eocene Ngimbang coaly shales are the proven source rocks for the East Java Basin oils and most of the gases. However, new geochemical analyses conducted for Kangean oils found very anomalous oil characteristics, diverting from the general characteristics of the East Java oilsof the Sepanjang Field (Sutanto et al., 2015; Musu and Sutanto, 2015) (Figure 9). Based on biomarkers and deuterium isotopes, the Kangean oils show stronger marine influence and reducing conditions although mixed with general characteristics of oils from terrestrial and oxidizing source rocks. The Kangean oils also show very low oleanane and sterane indexes, indicating that the source of oils could be pre-Cenozoic (possiblyCretaceous) in age. The presence of *Alisporites sp.*, an index taxa of the Lower Cretaceous in the sediments analyzed, is another strong indication that there is a Cretaceous source in the area.

Pristane and phytane ratio (Pr/Ph) of Sepanjang oils range from 1.5 to 2.5, Pr/n-C_{17} ranges from 0.1 to 0.3, and also supported by cross plot of Pr/n-C_{17} versus Pr/n-C_{18}, Sepanjang oils are believed to have strong marine facies (Figure 10).

Many terpanes in petroleum including triterpanes, oleananes and hopanes originated from bacteria (prokaryotic) membrane lipids (Ourisson et al., 1982). Triterpanes used in this study are biomarkers with fragment ion m/z 191. Most crude oils show C_{29}/C_{30} hopane m/z 191 peak ratios less than 1 for hydrocarbon originated from shales (deltaic or terrestrial depositional environments) especially with high terrestrial organic matter input. However, the ratio will be higher than 1, if the crude oils were originated from carbonates (Fan et al., 1987) (Figure 11).

Most researchers used triterpanes as a biomarker to determine source of organic matter and depositional environment (Peters et al., 2005). Other terpanes such as oleanane and hopane were also used in the study. Oleanane index (Oleanane/Olenane+C30hopane) is used to determine biostratigraphic age of hydrocarbon or sediments. An Oleanane index of more than 20% is diagnostic of Cenozoic or younger source rocks and related oils (Moldowan et al., 1994). Sepanjang oils show very low abundance of oleanane with an oleanane index of only 9.2 - 9.5 %, far less than the oleanane index of East Java oils which are mostly around 50 - 80 % (Satyana and Purwaningsih, 2003) (Figure 11).

Like triterpanes, most researchers use steranes with fragment ion m/z 217 for determining source of organic matter and depositional environment for hydrocarbon and sediments especially related to marine condition (Huang and Meinschein, 1979; Moldowan et al., 1985). Dominant C_{27} composition and high diasterane/sterane of Sepanjang oils indicate marine shaly source rocks (Figure 12). Ternary diagram using $C_{27}/C_{28}/C_{29}$ sterane distribution shows that Sepanjang oils were derived from sources with estuarine to open marine facies (Figure 13). This is different to most East Java oils which were sourced by terrestrial source facies (Satyana and Purwaningsih, 2003). Furthermore, C_{28}/C_{29} sterane can also be used for biostratigraphic age determination for crude oils from marine source rock with little or no terrigenous organic matter input. A ratio of sterane index that is less than 0.5 suggests Lower Paleozoic and older oils, whilst values between 0.47 - 0.7 are considered to show Upper Paleozoic to Lower Jurassic oils, and greater than 0.7 for Upper Jurassic to Miocene oils (Grantham and Wakefield, 1988). GCMS reveals that Sepanjang oils are a mixture from terrestrial to marine environments with sterane index ranging from 0.5 to 0.7.

The origin of the Sepanjang oils was also investigated using deuterium isotope for all n-alkanes of oils (Musu and Sutanto, 2015). δD values of n-alkanes in Sepanjang oils Samples revealed the hydrocarbon originated from marine source rock (marine shale), the values of δD mostly in between -100 to -150 ppt, indicating marine oils (> -200 ppt for marine, terrestrial will be < -200 ppt). Whereas most East Java oils are around -300 ppt (terrestrial) (Figure 14).

Recent analyses conducted by Sutanto et al. (2016) to establish the age of source rocks of Sepanjang oils involved applying biomarkers attained from the aromatic fraction of three oil samples from the Sepanjang field; namely Triaromatic Dinosteroid (TDS). Triaromatic dinosteroids are organic geochemicals derived from dinosterols, compounds known in modern organisms to be the nearly exclusive widely occurring products of marine dinoflagellates (Moldowan et al., 1996). They have been detected in Precambrian to Cenozoic rock samples, but are generally abundant in Mesozoic samples (Late Triassic through Cretaceous marine source rocks) (Figure 15). The abundant presence of the triaromatic dinosteroid biomarker in oil shows a marine source of Mesozoic age. Oils from Sepanjang wells were tested for their aromatic fraction TDS, and the results show a high number (above 0.80-0.84 or above 80 %) of Triaromatic Dinosteroid Index (TDSI) for all samples which may highly correlate to the Mesozoic age (Figure 16).

Various geochemical analysis on Sepanjang oils, including bulk properties, saturate and aromatic biomarkers (triterpane, oleanane, sterane, triaromatic dinosteroid), carbon and deuterium isotopes, all lead to a conclusion that Sepanjang oils were sourced by marine Mesozoic shales. Based on biostratigraphy and tectonic reconstruction, the source rocks should be Lower Cretaceous marine shales.

The Sepanjang oil field is located right on the Kemirian Terrace which is considered here to be the southern margin of the Paternoster-Kangean microcontinent. The margin is also the site of the major Sepanjang strike-slip fault, which may have provided a conduit to allow hydrocarbons derived from Lower Cretaceous source beds to migrate vertically through the Sepanjang Fault into the Eocene Ngimbang fractured carbonate reservoirs of the Sepanjang field.

The Emergence of a Mesozoic Petroleum System of East Java Basin

The new field and well data on geochronology and petrochemistry of the basement of East Java, East Java Sea, Makassar Straits and West Sulawesi do support the argument for a Gondwana-derived microcontinent, which tectonic reconstructions place in collision with Southeast and East Sundaland in mid-Cretaceous times. The area of collision subsequently became the sites of rifting and basin development during the Paleogene, with the South East Java Forearc, East Java, South Makassar, North Makassar, West Sulawesi, and possibly Eastern Kalimantan Basins forming at this time. The updated tectonic reconstruction of Satyana, (2014a, 2014b, 2015) provides one solution to how this collision and subsequent basin development took place. Based on the similarities in geochronologic age distribution and tectonic reconstruction, it is suggested that these microcontinents were derived from northern Gondwanaland, presently the NW Shelf of Australia

(Figure 17), as has been previously proposed (e.g. Hall, 2012)..

Deep seismic data recently acquired by ION-GXT at East Java Sea and the Makassar Straits, and by TGS in the South East Java Forearc show the presence of a pre-Cenozoic (Mesozoic and possibly Paleozoic horizons) section, bedded and deformed, showing the presence of sedimentary rocks in the area of the proposed microcontinents. These sedimentary sections underlie the classical basement picking horizonand thus the presence of sedimentary packages of Mesozoic and possibly Paleozoic age below this eroneous basement pick seems probable, and provide an interesting and yet to be explored opportunity with similarities to those prolific plays on the NW Shelf of Australia.

The presence of marine oil in Sepanjang field - Kangean area, suggested by geochemical data to be sourced by Lower Cretaceous marine shales, enhances significantly the Mesozoic prospectivity in areas where Gondwana-derived microcontinents are believed to have collided against SE and East Sundaland. The Sepanjang field is structurally positioned on the southern margin of the Paternoster-Kangean microcontinent where its Lower Cretaceous sedimentary section has generated oils and fed Eocene fractured carbonate reservoirs of the Sepanjang Field vertically through faults. The Sepanjang Lower Cretaceous oils provide the key to assess the concept of Mesozoic petroleum systems in the East Java Basin. Indeed, this potentially opensother areas which are interpreted to lie on broad microcontinents around East Java (South East Java Forearc, South Makassar, North Makassar, Western Sulawesi, and Eastern Kalimantan) for further examination with regards to the possibility of Mesozoic petroleum.

The presence of a generating source in the Mesozoic sections of the East Java Basin is evidence of an active petroleum system. Matured source is the most significant element in the petroleum system because it is the matured source which generates petroleum. No source no petroleum, although we have excellent reservoirs and good traps.

The newly identified Lower Cretaceous marine shale source rocks, have generated marine oils which are now trapped in structures, such as in the Sepanjang field. This has not been identified before even though the East Java Basin has been explored for almost 50 years in modern times. The presence of new source rocks will enrich the petroleum prospectivity of the East Java Basin which, until now, has been thought to havebeen soley dependent on the Eocene Ngimbang coaly shales.

A ‘new’ petroleum system for the East Java Basin, partly involving Mesozoic elements, can be constructed. At the time of this manuscript, very little detail is known about each element and process of the system, but deep seismic data are interpreted to show sedimentary sections and structures, considered Mesozoic in age –proven in Kangean area among others - overlying the microcontinents which are reported to have collided with SE and East Sundaland during the mid-Cretaceous. An analogue to the Mesozoic petroleum system of NW Shelf Australia is suggested here, based on the tectonic reconstructions which suggest the microcontinents and pre-Cenozoic sedimentary cover were derived from this region. The following is a preliminary discussion on each element and process of the Mesozoic petroleum system of the East Java Basin (Figure 19).

Source Rocks

Oil geochemistry of the Sepanjang field, discussed above, shows the presence of active pre-Cenozoic source rocks in the Kangean area, deposited overlying the southern margin of the Paternoster-Kangean microcontinent. Based on geochemical characteristics of generated oil (Sutanto et al., 2015, 2016), biostratigraphy, and tectonic reconstructions (Satyana, 2014a, 2014b, 2015); it is considered that the source rocks are Lower Cretaceous marine shales. Tectonically, the section was a syn-drift tectonostratigraphic unit deposited when the microcontinent departed to its present area. The microcontinent detached from northern part of Gondwanaland (presently NW Shelf Australia) in Late Jurassic (Metcalfe, 2013) and collided SE and East Sundaland in mid-Cretaceous time (Granath et al., 2010; Satyana, 2014a, b).

When reviewing the deep seismic data, it is evident that the pre-Cenozoic section is not restricted to the Lower Cretaceous marine shale interval. Indeed, the seismic clearly shows a sedimentary section of around 3.5 seconds TWT in the East Java Sea and South Makassar areas, which are considered as Mesozoic-Paleozoic sedimentary sections (Emmet et al., 2009). Similar thicknesses of age-equivalent units are also recorded in the South Java Outer Forearc (Deighton et al., 2011)., and perhapsanalogue sections in the NW Shelf of Australia could be considered when assessing the pre-Cenozoic sections in East Java (Figure 18).

Traditional and well-known Mesozoic source rock systems of the NW Shelf are found within the Middle Jurassic Plover Formation and the Late Jurassic Flamingo Group. While the primary play in the region has been hydrocarbons sourced from Lower to Middle Jurassic Plover sediments (mixed Type 2 and Type 3 kerogens), it is considered that both younger and older oil-prone source rock successions may have generated hydrocarbons in NW Shelf (Barber et al., 2003).

As for the Paleozoic source rocks, based on analogues with the Bonaparte Basin and Goulburn Graben to the south, Barber et al. (2003) suggest the Paleozoic basins could contain high quality and mature oil-prone source rocks of Cambrian, Devonian and Carboniferous age. They note that numerous oil, bitumen and gas shows have been documented from the Paleozoic succession in the graben, notably at Arafura-1, Goulburn-1, Kulka-1and Tasman-1, the most significant being at Arafura-1, where live oil was recovered over a 425m interval within fractured Ordovician dolomites and upper Devonian dolo-siltstones. They highlight that the latter shows have been typed by biomarkers to oil mature Mid-Cambrian Jigaimara Formation organic rich shales, which exhibit mean TOC's of 3% and a HI of 149. Organic rich sediments of Late Devonian age were also penetrated in Arafura-1 (TOC: 3.86%). From Petrel Basin analogues, Barber et al. (2003) propose that oil-prone source rocks would be expected along the northern Australian margin in the Lower Carboniferous Milligans Formation and also deltaic sequences in the Permian (Barber et al., 2003) (Figure 18).

To assess the quality of transported Mesozoic and Paleozoic source rocks in SE and East Sundaland's microcontinents two methods can be implemented: (1) examination of seismic characters of the sections and (2) assessment through paleogeographic reconstruction (i.e. restoring the microcontinents to the original areas) before referring to geochemical characteristics of age-equivalent sections in the NW Shelf of Australia.

Maturation of source rocks based on aromatic methyl phenanthrene biomarkers of Lower Cretaceous oils in Sepanjang field (calculated Ro or Rc equivalent to be 1.0 %) is considered to start in Miocene times. This implies that Mesozoic and Paleozoic source horizons in these microcontinents have been taken through the oil and gas window since the Miocene, actively generating oils and gases when organically rich. From the limited data available, over maturity appears not to be problem for most of the Mesozoic and Paleozoic sections in SE and East Sundaland microcontinents. The areas are also quite isolated from Cenozoic tectonics, avoiding the possibility of tectonic overprint such as that seen in the Mesozoic and Paleozoic sections of Sumatra.

Reservoir Rocks

The oils generated from Lower Cretaceous marine shales in the Kangean area are interpreted to have charged Eocene fractured carbonates of the Ngimbang Formation. It is possible that this was facilitated bya fault conduits, such as the Sepanjang Fault which directly connects pre-Cenozoic units with the overlying section.. Indeed, the possibility of oils or gases charging Mesozoic and Paleozoic sections overlying the microcontinents is reasonable, providingreservoir qualities are good. With this in mind, the possible analog sections in the NW Shelf could be considered, (Barber et al., 2003- Figure 18)and provide insight to reservoir character. There are numerous intervals within the Mesozoic and Paleozoic sections of the NW Shelf, both productive and potential. These include: sandstones and carbonates of the Cambrian-Ordovician Goulburn Group, sandstones of the Carboniferous Weaber and Kulshill Groups, sandstones and carbonates of the Late Permian Kinmore Group, sandstones of the Middle Triassic Troughton Group, sandstones of the Middle Jurassic Troughton Group (Plover Formation), and sandstones of the early Late Jurassic Lower Flamingo Group (Elang/Laminaria Formation).

In order to assess the quality of transported Mesozoic and Paleozoic reservoir rocks overlying SE and East Sundaland's microcontinents, two methods can be applied (1) examination of seismic characteristics and (2) assessment through paleogeographic reconstructions (i.e.restoring the microcontinents to the original areas) before referring to reservoir characteristics of age-equivalent sections in the NW Shelf of Australia.

Emmet et al. (2009) observed that the well-bedded sections between some seismic horizons thicken from north to south, and show some evidence of 'cut and fill' sedimentation, suggesting deltaic deposition, followed by a largelyterrestrial section. If this is so, the sections may represent a transgressive-regressive mega-cycle.

Collision of the microcontinents against SE and Southeast Sundaland may open the possibility of fractured, pre-collision reservoirs due to intensive deformation. Therefore, originally tight sedimentary rocks and crystalline basement may also form important reservoirs if fractured.

Sealing Rocks

Paleozoic and Mesozoic basinal shales, regionally or locally deposited, are likelyinterbedded with reservoirs of each sedimentary group discussed above, and thus, act as sealing rocks/traps. Sections of shales deposited during Paleogene and Neogene after the Cenozoic sedimentary basins developed overlying these Pre-Cenozoic sections will provide additional sealings.

Overburden Rocks

As thick as 5 km Pre-Cenozoic sections in the East Java Sea and South Makassar Straits (Emmet et al., 2009) and 3.5seconds TWT of Pre-Cenozoic sections in South Java Outer Forearc (Deighton et al., 2011), with an additional 1 to 3.0 seconds TWT of Cenozoic sections in these areas should provide enough thickness of overburden to mature the source rock intervals at various levels within the Mesozoic and Paleozoic sections. The thermal characters will be controlled by thermal conductivities of each formation from Paleozoic to Cenozoic, in addition to heatflow from the basement (mostly continental due to microcontinents), and cooling from the overriding water column (shallow sea) or thick (deep sea).

Based on the aromatic methyl phenanthrene index (MPI) of Lower Cretaceous oils in the Sepanjang field, which is equivalent to Ro source maturity of 1.0 %, it is known that the generation of the oil from Lower Cretaceous sources in this area took place in intra-Miocene times, implying that the source needs Paleogene and early Miocene overburden to generate the oil. This also implies that older sources (Jurassic and older) generated oils could be earlier.

Traps

Structural and stratigraphic trapping could develop in the Mesozoic and Paleozoic sedimentary covers of the microcontinents. Stratigraphic trapping may form due to change in depositional pattern such as lateral or vertical facies changes. Structural traps may have begun to develop during deformation of the Jurassic and older sections prior to rifting of the microcontinents away from the Australian margin.. Collision of the microcontinents during the mid-Cretaceous would have then provided the compressional regime needed to produce the classic inversion structures that contain much of the oil and gas in the region. Deep seismic data in the East Java Sea, South Makassar, and the South East Java Forearc, show the possibility of depositional change, and folded, faulted seismic horizons, , and erosional truncation represented by the o significant unconformity separating pre-Cenozoic and Cenozoic units. In addition, various traps may have formed in the pre-Cenozoic sedimentary covers associated with original deposition, collision, uplift, and erosion episodes. Possible traps of this character can be interpreted from the deep seismic data.

Migration Charging, and Preservation of Accumulation

As in the majority of petroleum systems, oil and gas are expelled from source rocks, and migrate along carrier beds or discontinuities such as faults towards lower pressure areas in the subsurface and eventually trapped in viable reservoirs. This scenario is proposed for the Lower Cretaceous oils which are now reservoired within fractured Eocene carbonates of the Sepanjang field. This is supported by interpretations of the Mesozoic and Paleozoic sections from the deep seismic data which show the presence of tilted beds and faulted beds that may have influenced the migration of oils from kitchen to reservoir.

Preservation of accumulation in Mesozoic and Paleozoic sections appears to relate to breaching of traps, biodegradation or meteoric water washing, CO_2 pollution, or thermal degradation. All of these processes assume that accumulations of petroleum had occurred before the collision of microcontinents took place in mid-Cretaceous time. The collision possibly breached the existing plays by forming faults, deforming traps, uplifting the structures, and eroding elements of the section (as seen on seismic sections), thusopening the possibility for biodegradation or water washing. The possibility of CO_2 pollution and thermal degradation would require the accumulations to be subsided due to later tectonic episodes and burial by Cenozoic sediments. CO_2 gas generation may occur if there are Mesozoic or Paleozoic carbonates which subsided into the overmature window and degraded thermally, releasing CO_2. This may result in other gas accumulations being pollutedif the accumulation connects to the area of CO_2 generation.

Oil and gas accumulation at depth can also thermally degrade (oil becoming gas, and gas stripped by more mature gas) However, if the process of generation, migration and accumulation of petroleum within the Mesozoic and Paleozoic sections occurred in Cenozoic from Lower Cretaceous marine shales in Miocene, and migrated into Sepanjang field, the process of accumulation degradation discussed above is possibly not an issue..

CONCLUSIONS

1. There are some Australian/Gondwana-derived microcontinents which collided with SE and East Sundaland in mid-Cretaceous times. The microcontinents brought with them their thick (Australian) Paleozoic to Mesozoic sedimentary cover, as shown by deep seismic data in East Java Sea, South Makassar, and South East Java Forearc Basins.

2. Detailed oil geochemistry data, including bulk properties, saturate and aromatic biomarkers, carbon and deuterium isotopes, have indicated thatthe Sepanjang field in the Kangean area – was charged since Miocene times by oil from Lower Cretaceous marine shales, proving an active Pre-Cenozoic petroleum system in the East Java Basin.

3. Based on deep seismic data, geochemical analysis, tectonic reconstruction, and possible analogue sections in the NW Shelf of Australia, a Pre-Cenozoic petroleum system of East Java Basin can be constructed. Elements of sources, reservoirs, seals, and overburdens possibly developed, with one source interval of Lower Cretaceous marine shales proven as a generating oil. Trap formation may relate to pre-rift and drift deformation (i.e. before Early Cretaceous), during collision (mid-Cretaceous), or during Cenozoic deformation coeval with tectonic episodes of the East Java Basin. Hydrocarbon generation as revealed by the Lower Cretaceous marine shale-sourced oil took place in Miocene times or earlier for older sources. Migration took place both laterally and vertically, charging available traps. Preservation may relate to tectonic overprinting during the Cenozoic.

4. There is still much to do to better understand the Pre-Cenozoic petroleum system of the East Java Basin. More exploration surveys are needed. Nevertheless, the preliminary data and interpretations presented here and in previous publications, collectively suggest an active Pre-Cenozoic petroleum system. Therefore further exploration is warranted.

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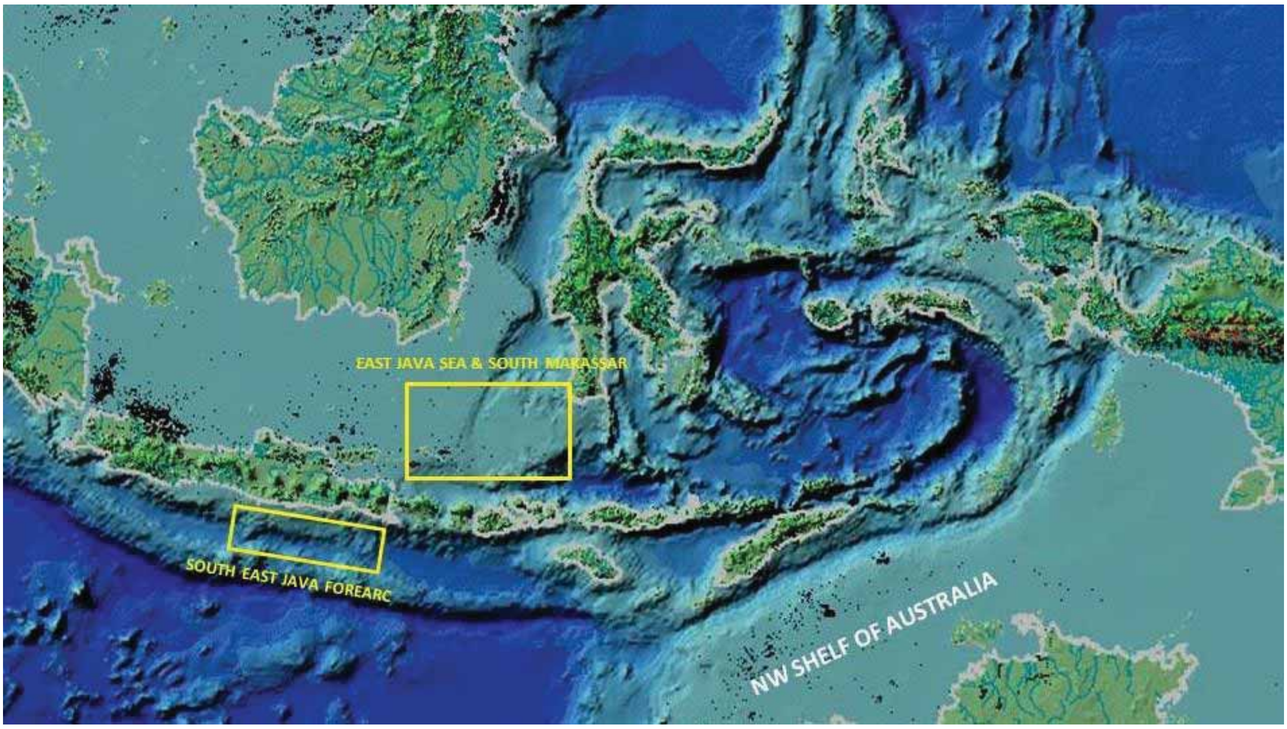

Figure 1 - Location of study areas in rectangles (East Java Sea - South Makassar, and South East Java Forearc). Location of NW Shelf of Australia discussed in the paper is also indicated.

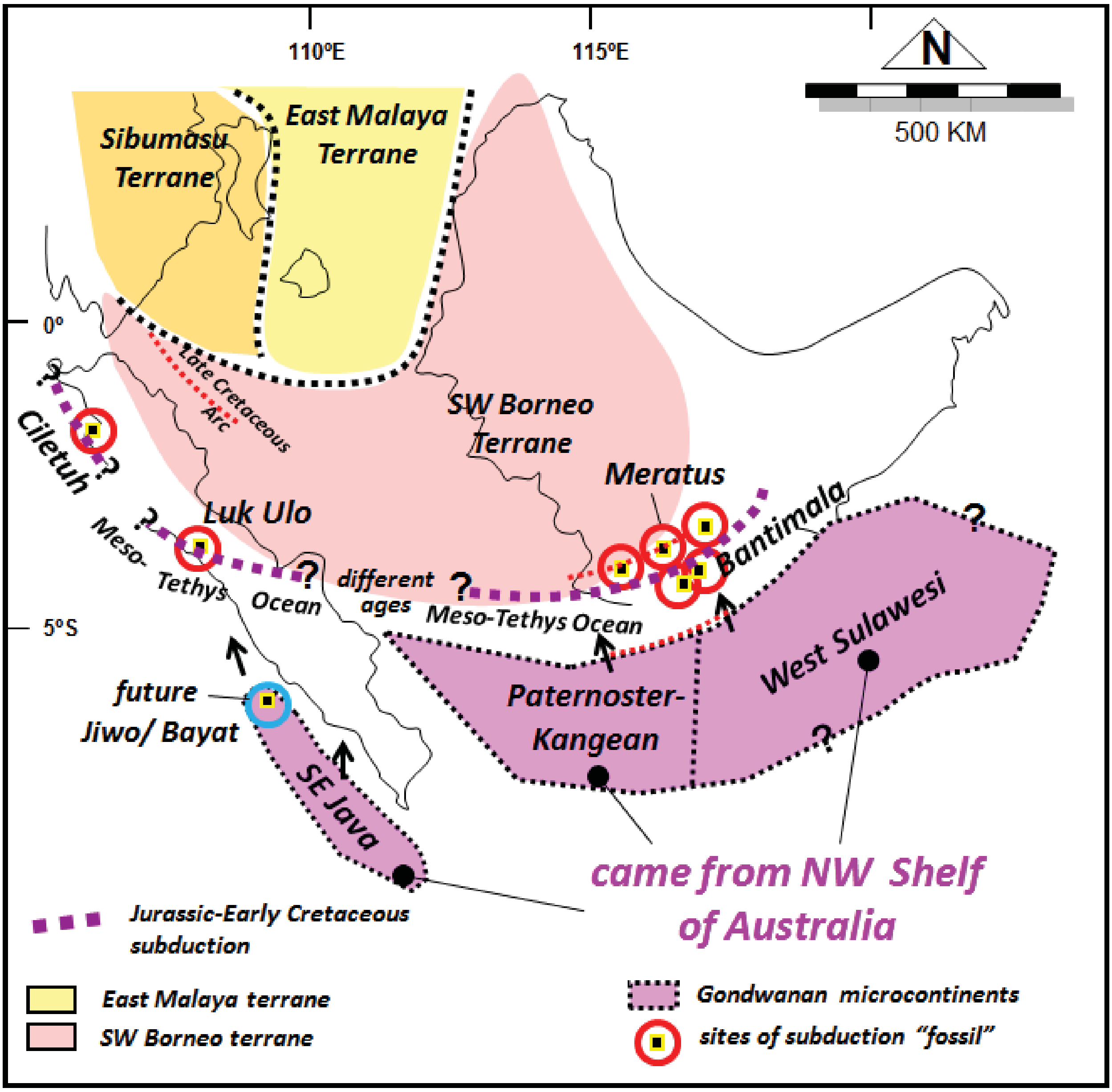

Figure 2 - New tectonic reconstruction of SE and East Sundaland in upper Early Cretaceous, providing new regional framework of petroleum geology of SE Sundaland, mainly for pre-Tertiary objectives. Pre-Tertiary microcontinents are considered derived from NW Shelf of Australia, rifted in Late Jurassic and drifted during Early Cretaceous and collided Sundaland in mid-Cretaceous time. The microcontinents are considered brought Paleozoic and Mesozoic sedimentary covers where Pre-Tertiary petroleum system is expected to develop (Satyana, 2014a, b, 2015).

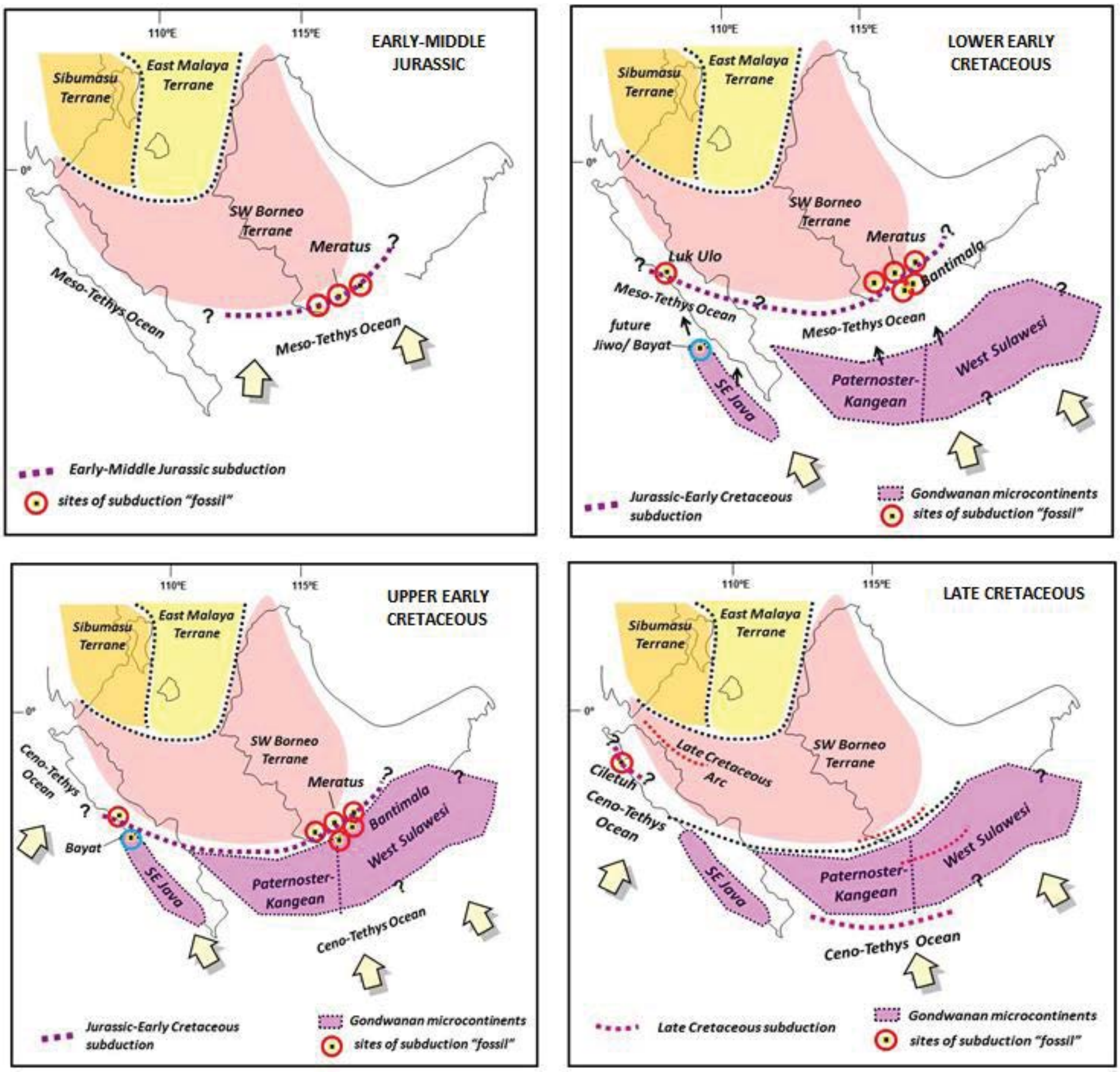

Figure 3 - New tectonic reconstruction of SE and East Sundaland from Early Jurassic-Late Cretaceous, typified by subduction of Meso-Tethys oceanic plate and accretion during Early Jurassic to Early Cretaceous, collision of some Gondwanan microcontinents at around mid-Cretaceous, and ended with subduction of Ceno-Tethys oceanic plate in Late Cretaceous (Satyana, 2014a, b, 2015).

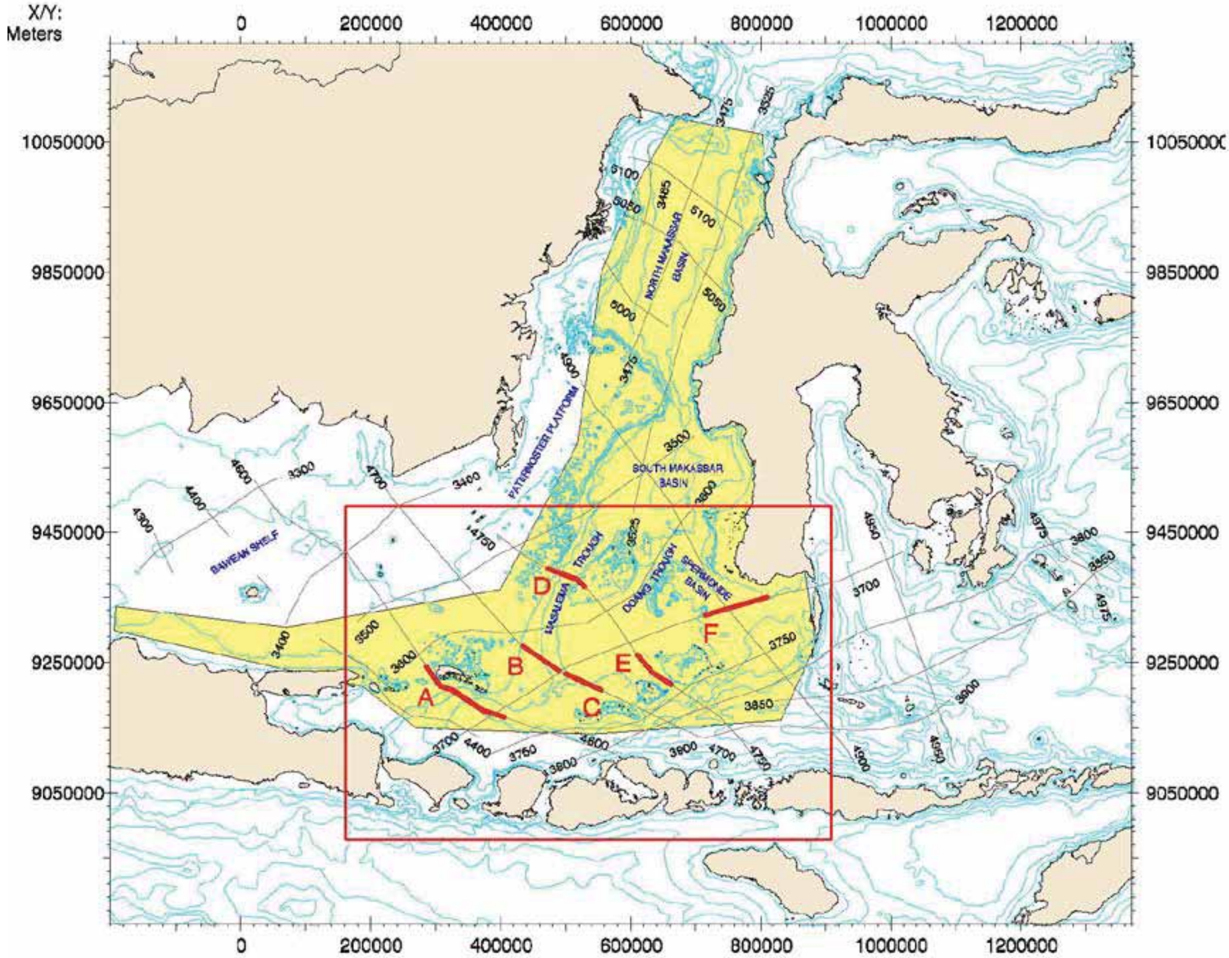

Figure 4 - Basemap showing location of JavaSPAN seismic survey profiles. Yellow polygon represents region of terranes added to Sundaland in the Cretaceous and Tertiary (Granath, et al. 2009). Red inset shows focus area on the East Java terrane(s) (Emmet et al., 2009).

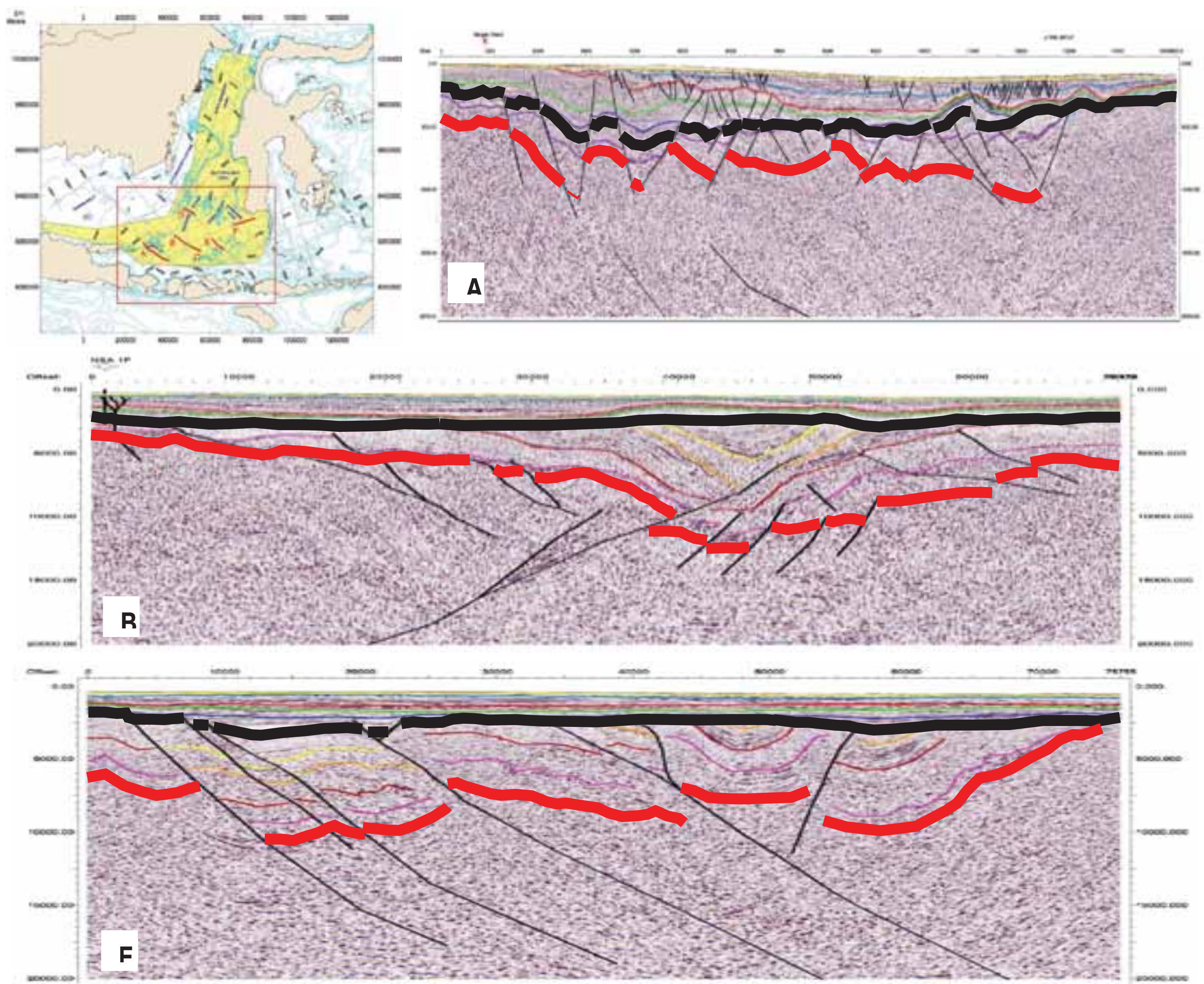

Figure 5 - Some deep seismic sections of JavaSPAN at Kangean area, East Java Sea. The bold black horizon is base Middle Eocene, commonly interpreted as top of Basement in former time on shallow seismic data. Bold red horizon is considered as top of the crystalline Basement. Based on these new deep seismic data, there are around five km of pre-Tertiary sedimentary sections considered Mesozoic and Paleozoic in ages remain unexplored (modified after Emmet et al., 2009).

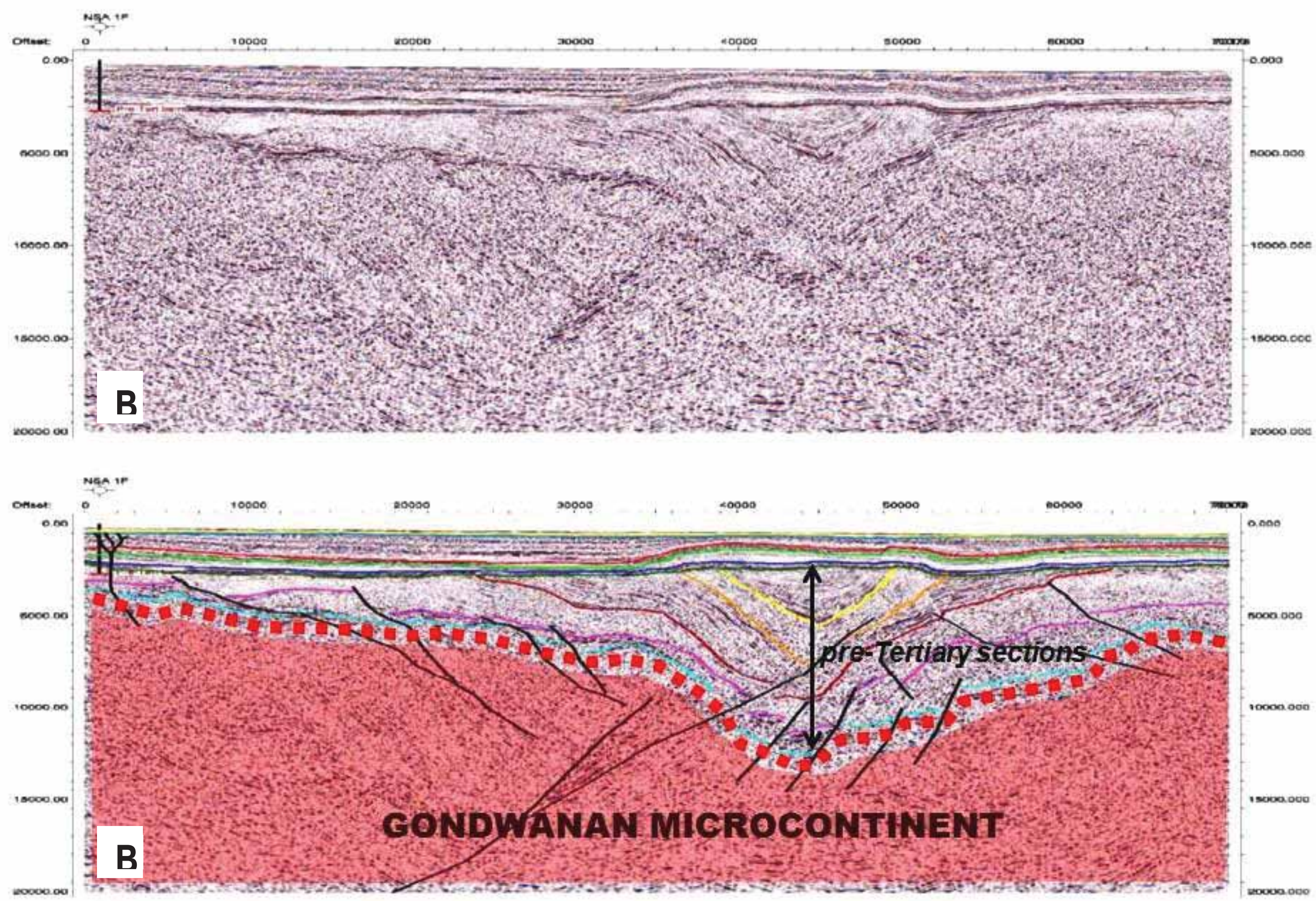

Figure 6 - Seismic line B in Figure 4, showing the Tertiary and Pre-Tertiary sedimentary rocks covering the Gondwanan microcontinent. This profile is oriented NW-SE and is located just north of a region-wide trend of strongly inverted Paleogene half grabens. The strata beneath regional mid-Eocene unconformity surface are believed to have affinity to the stratigraphy of the NW Shelf of Australia. The following speculative horizons are yellow = Middle Cretaceous, orange = Oxfordian? (Middle Jurassic); may represent the departure unconformity from Australia, dark brown = Triassic; the interval from dark brown to orange looks like a deltaic sequence that progrades from left to right, and magenta = top Paleozoic or top Permian; the thin interval between the magenta and cyan/red horizons has an inverted syn-rift character (modified after Emmet et al., 2009).

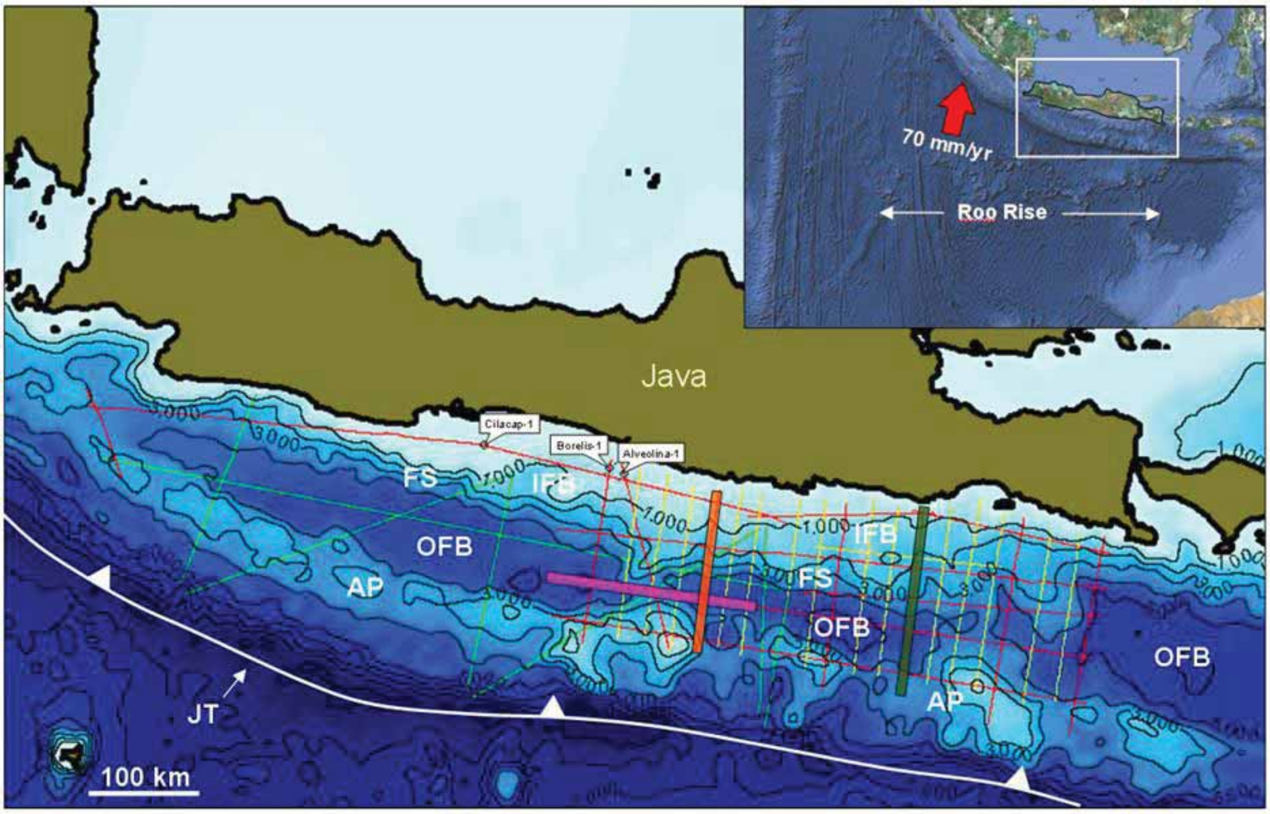

Figure 7 - Location of Southeast Java Basin. Seabed TWT contours at 1 second intervals. TGS seismic surveys: green SJR-09, yellow SJR-10 and red SJi-10. Five major structural zones are indicated as follows: JT = Java Trench; AP = Accretionary Prism; OFB = Outer Forearc Basin; FS = Forearc Slope and IFB = Inner Forearc Basin. Red, pink and green narrow rectangles show locations of seismic sections displayed on Figure 8 (Deighton et al., 2011).

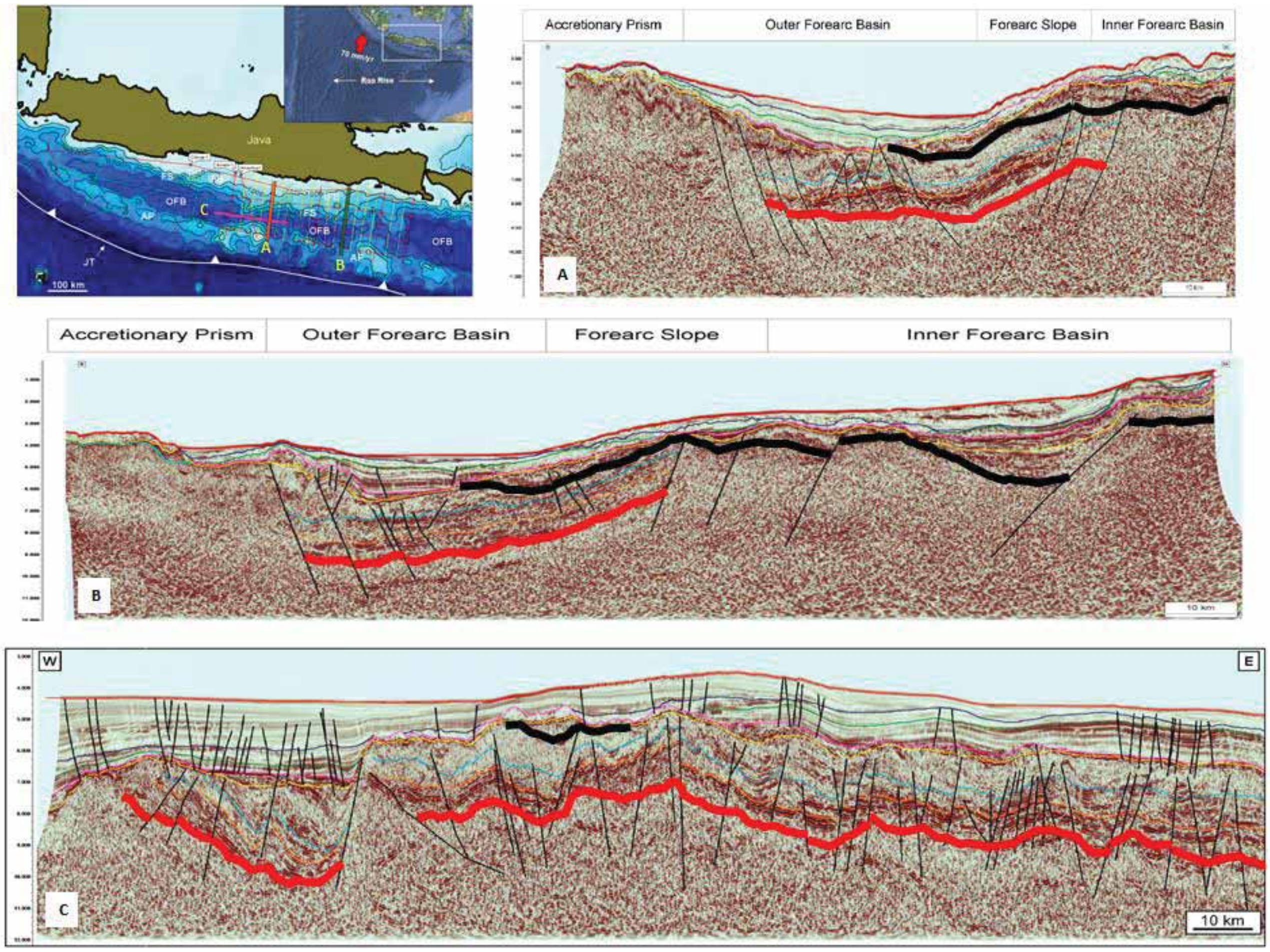

Figure 8 - Seismic lines A, B, C of South East Java Forearc. Bold black horizon is base of Tertiary, bold red horizon is top of Basement. The possible Mesozoic section can clearly be seen beneath the Outer Forearc Basin and Forearc Slope below 5 seconds TWT of dip lines A and B, while a probable Paleogene half-graben is present beneath the Inner Forearc Basin on line B. Strike seismic line C showing flat bedded to slightly deformed Late Tertiary sediments of the outer forearc basin overlying more deformed Paleogene and faulted older sediments of possible Mesozoic age (modified after Deighton et al., 2011).

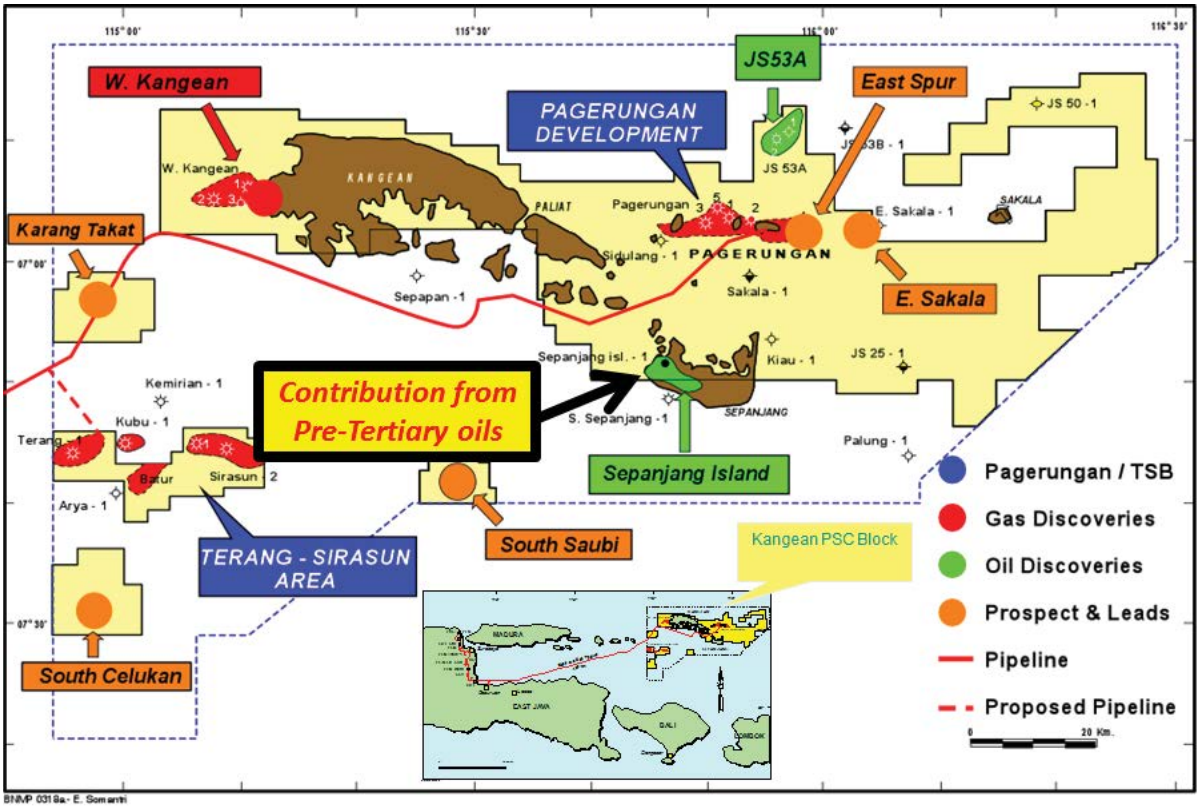

Figure 9 - Location of fields in Kangean area, East Java Sea. The Sepanjang field is discussed in detail for its oil characters showing a contribution from pre-Tertiary (Lower Cretaceous) source rocks.

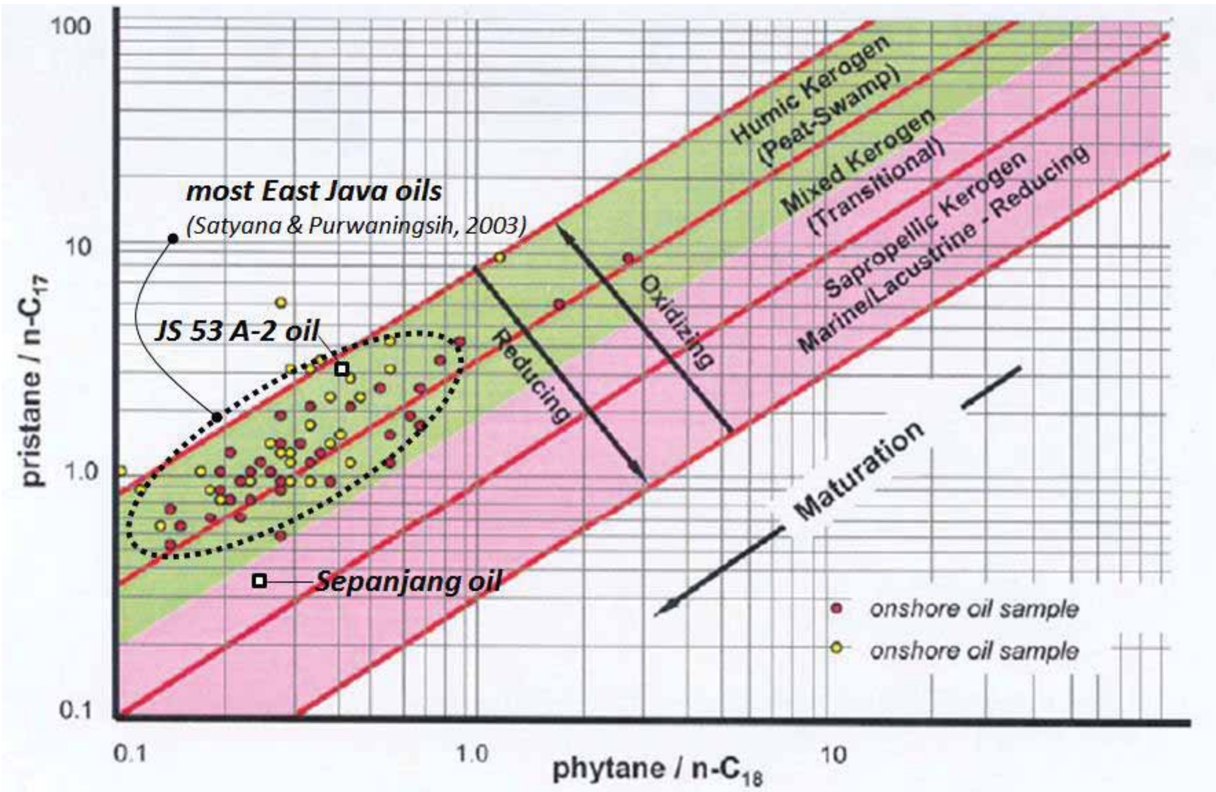

Figure 10 - Cross plot of pristane and phytane to normal alkane showing kerogen input, source facies and reduction-oxidation conditions. Note that the Sepanjang oil is beyond the general group of East Java oils, characterized by terrestrial peat-swamp humic kerogen, whereas Sepanjang oil is more marine contributed by sapropelic kerogen.

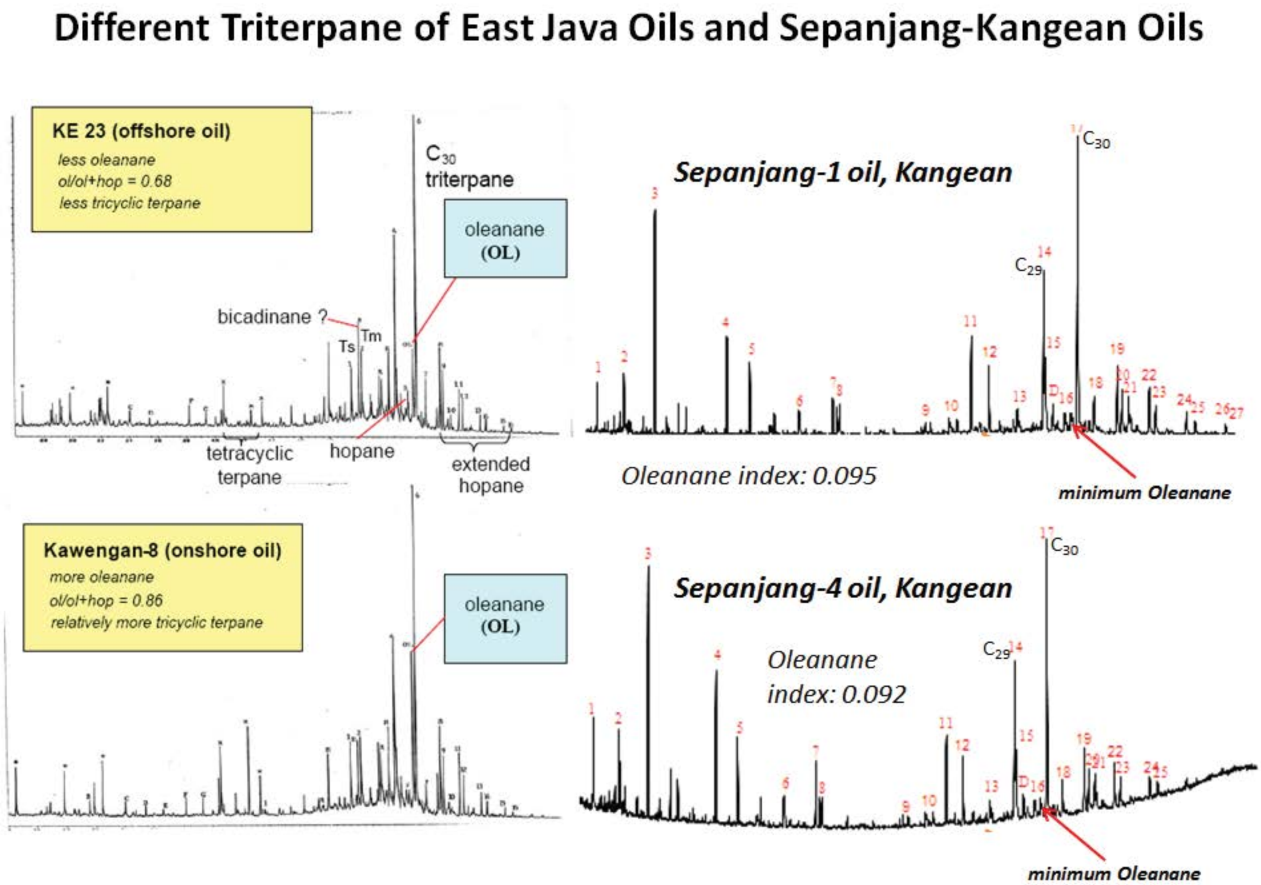

Figure 11 - Triterpane m/z 191 distribution of KE-23 and Kawengan, representing general characteristics of East Java oils (Satyana and Purwaningsih, 2003) and Sepanjang oils (Sutanto et al., 2015). Oleanane index (oleanane/oleanane + hopane) of the two groups are much different. Oleanane index > 0.20 indicates Tertiary source rocks (Moldowan et al., 1994). Very low oleanane index of Sepanjang oils (< 0.20) may show a contribution from marine pre-Tertiary source rocks. Low ratio of C_{29} norhopane to C_{30} hopane indicates shaly source rocks.

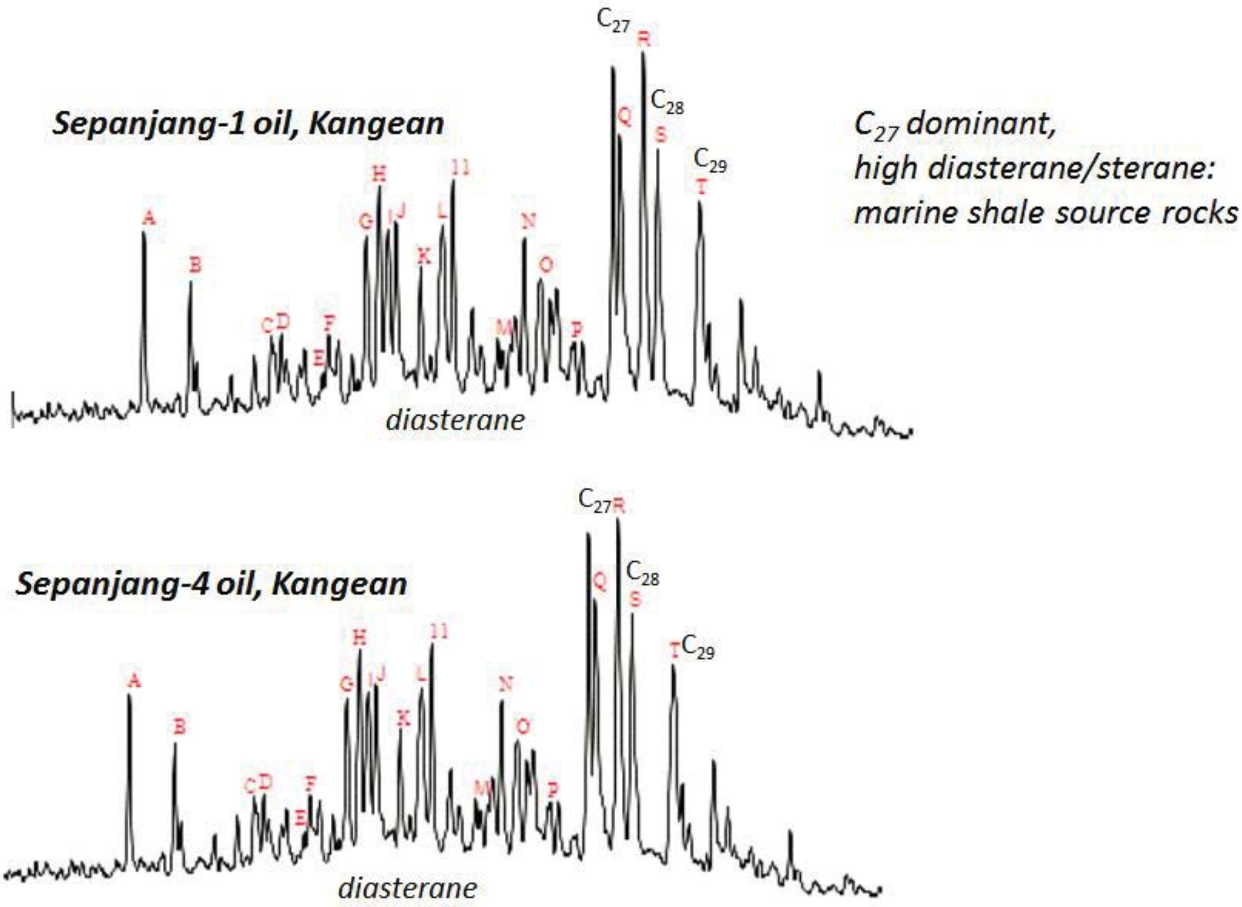

Figure 12 - Sterane m/z 217 distribution of Sepanjang oils showing dominant C_{27} composition and high diasterane/sterane indicating marine shaly source rocks (Sutanto et al., 2015).

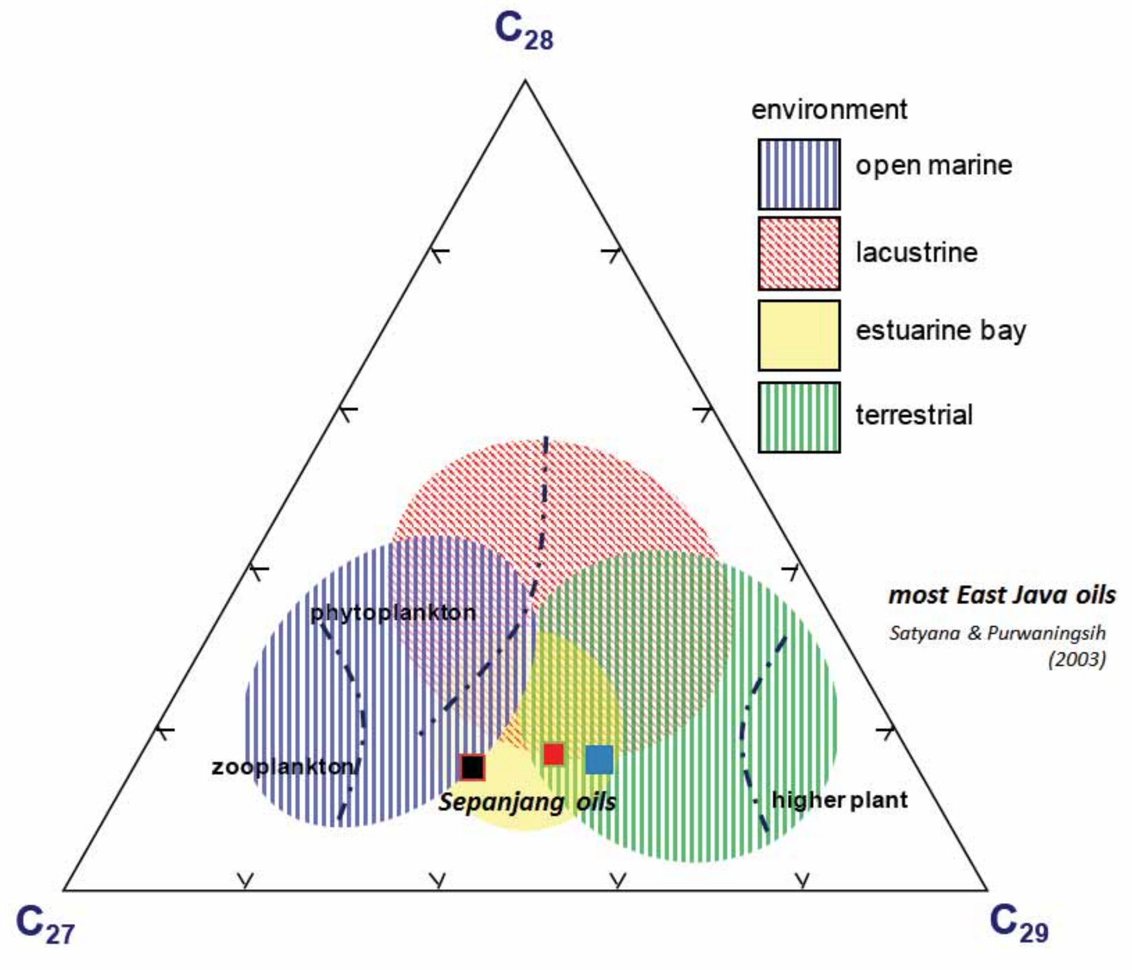

Figure 13 - C_{27}-C_{28}-C_{29} sterane distribution showing source facies of East Java oils. Note that Sepanjang oils are beyond the general area of East Java oils which are mostly terrestrial. Sepanjang oils have estuarine to open marine facies (Sutanto et al., 2015).

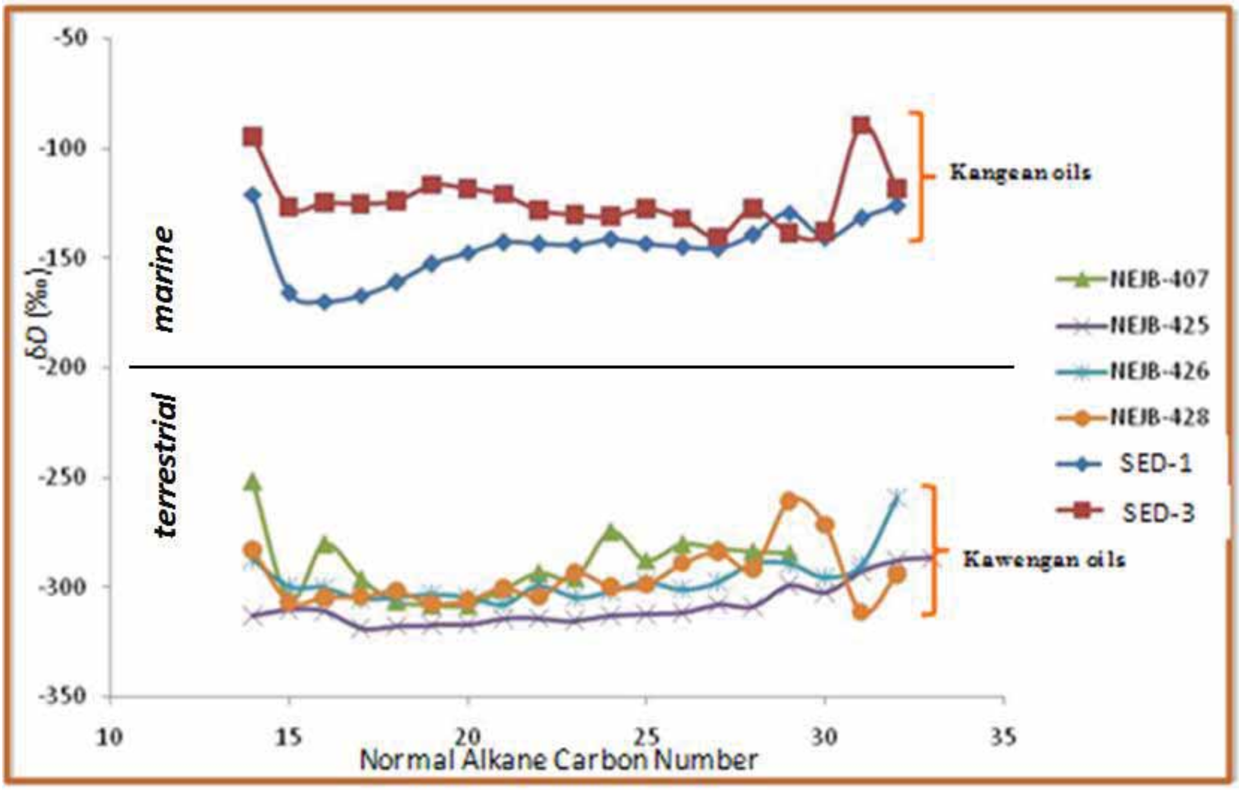

Figure 14 - Detailed δD (‰) profile of Sepanjang oil and East Java oils, represented by Kawengan oil on normal alkanes carbon number. Obvious difference immediately shows up, Sepanjang oil is marine (δD > -200 ‰), whereas Kawengan oil is terrestrial (δD < -200 ‰) (Musu and Sutanto, 2015)

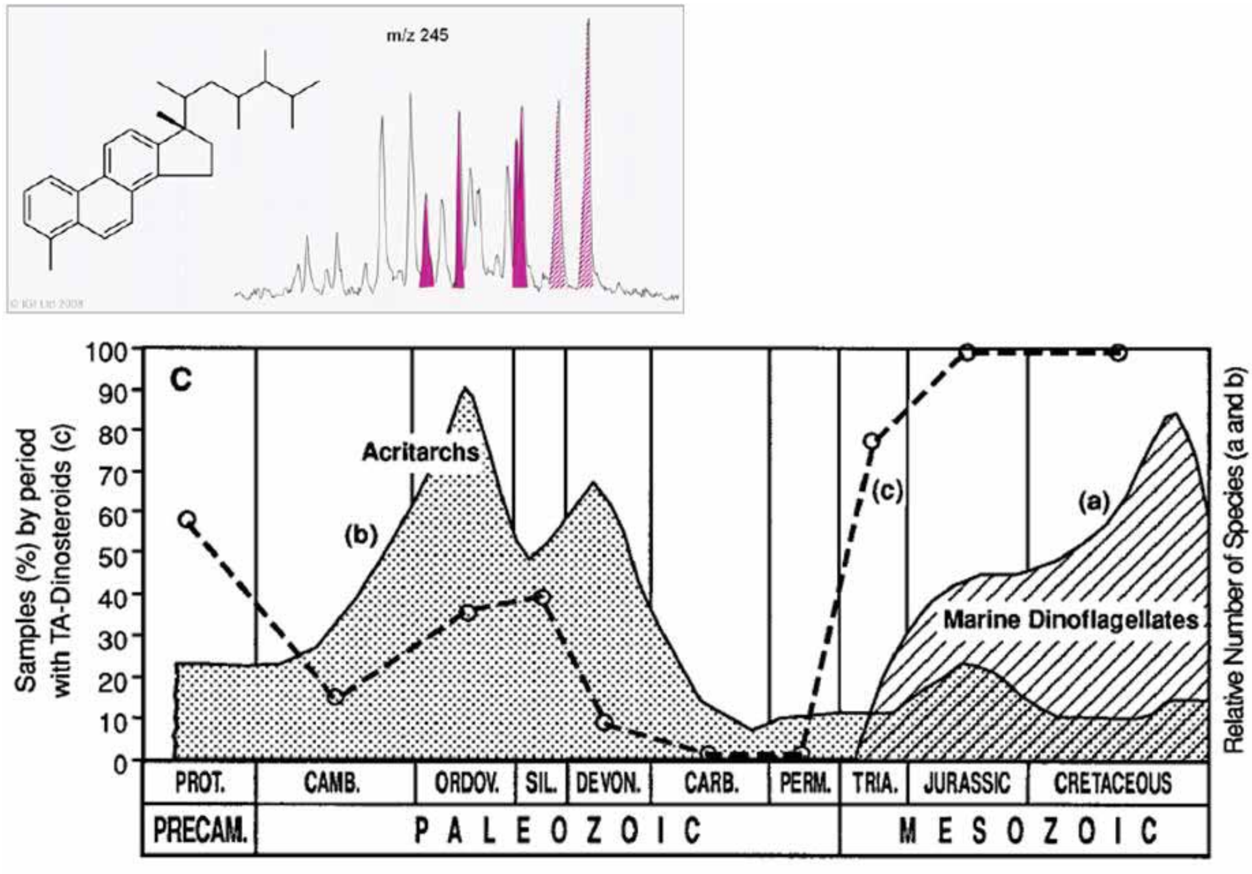

Figure 15 - Schematic representations of relative numbers of species of (a) dinoflagellate cysts and (b) acritarch cysts. Circles and dashed lines (c) give frequency of occurrence of detectable triaromatic dinosteroids in samples from each geologic time period (Moldowan et al., 1996). Inset shows triaromatic dinosteroids (shaded) identified in an m/z 245 mass chromatogram of the aromatic hydrocarbon fraction of an oil.

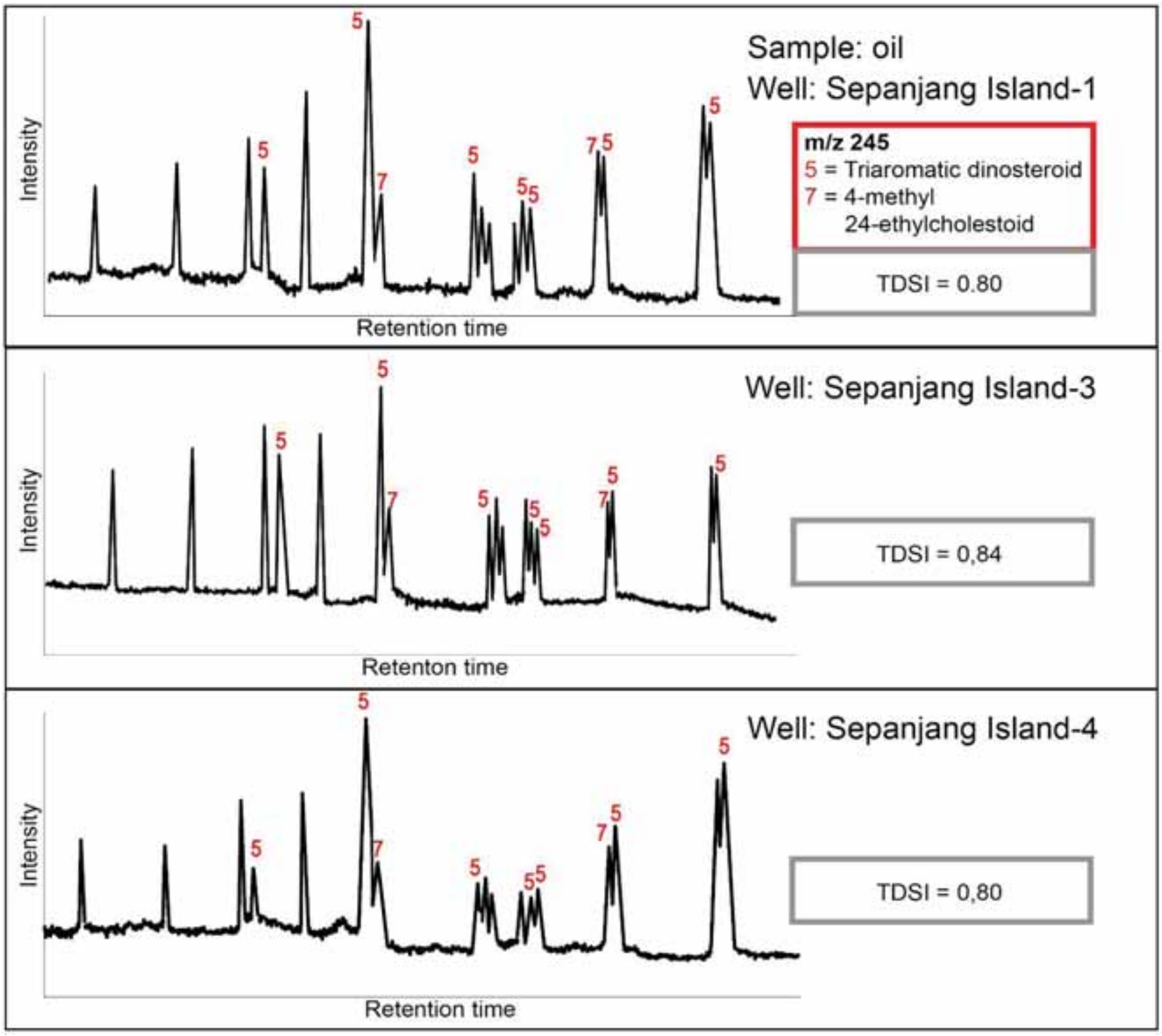

Figure 16 - Triaromatic dinosteroid m/z 245 distribution for Sepanjang oils showing peaks of triaromatic dinosteroid and 4-methyl-24-ethylcholestoid. Triaromatic Dinosteroid Index calculated indicates very high percentage which correlate to Mesozoic age (Sutanto et al., 2016).

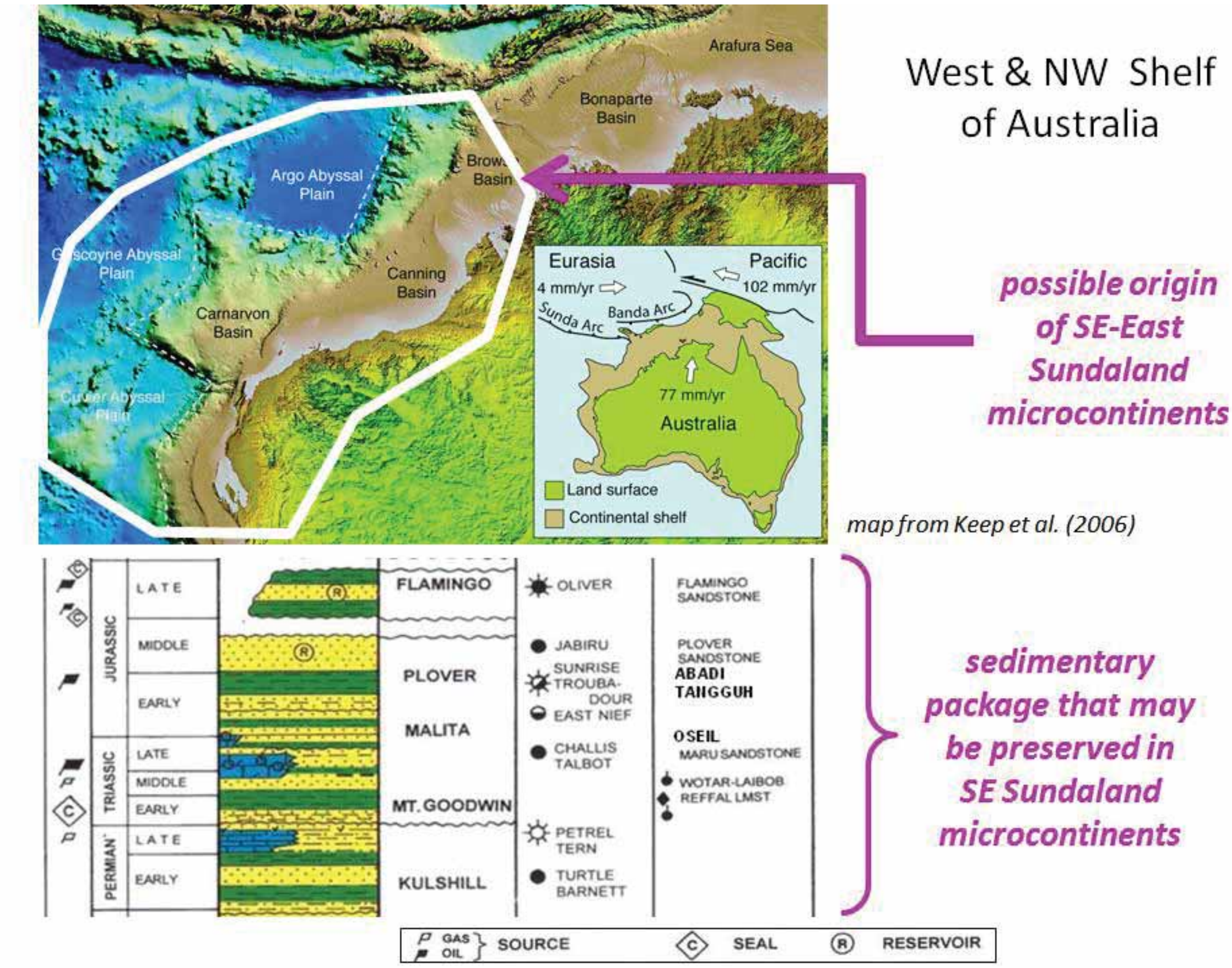

Figure 17 - West and NW Shelf of Australia is considered as original areas for microcontinents colliding SE and East Sundaland. Paleozoic and Mesozoic sedimentary rocks until Middle-Late Jurassic could develop on the microcontinents before departing to their present areas. Permian to Jurassic sequences of NW Shelf of Australia are shown, and are prolific for petroleum.

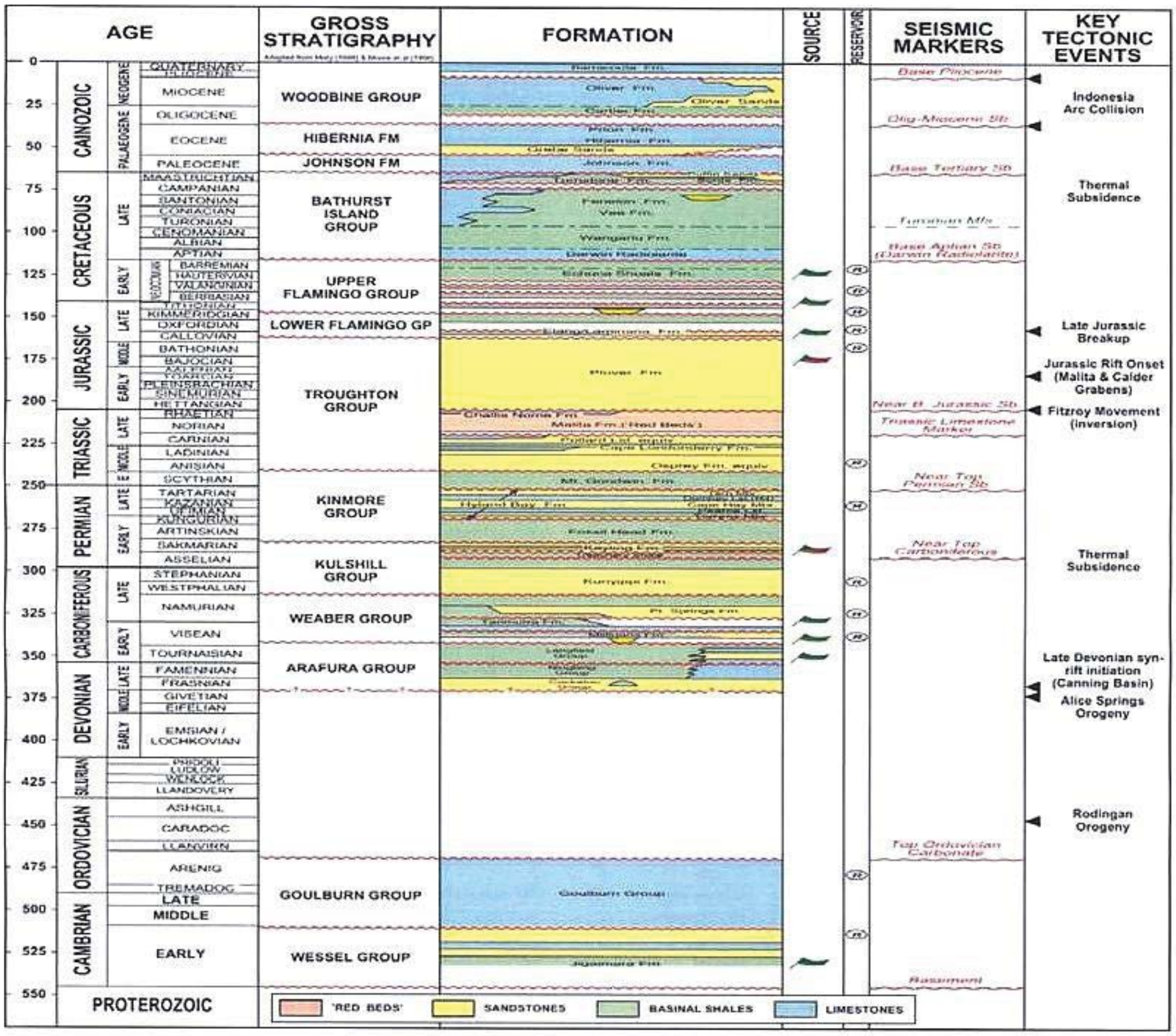

Figure 18 - Late Paleozoic to Recent regional stratigraphy and its petroleum system elements, Bonaparte Basin, NW Shelf of Australia (Barber et al., 2003) can become an analogue for Paleozoic and Mesozoic sections of the northern Gondwanan microcontinents colliding SE and East Sundaland.

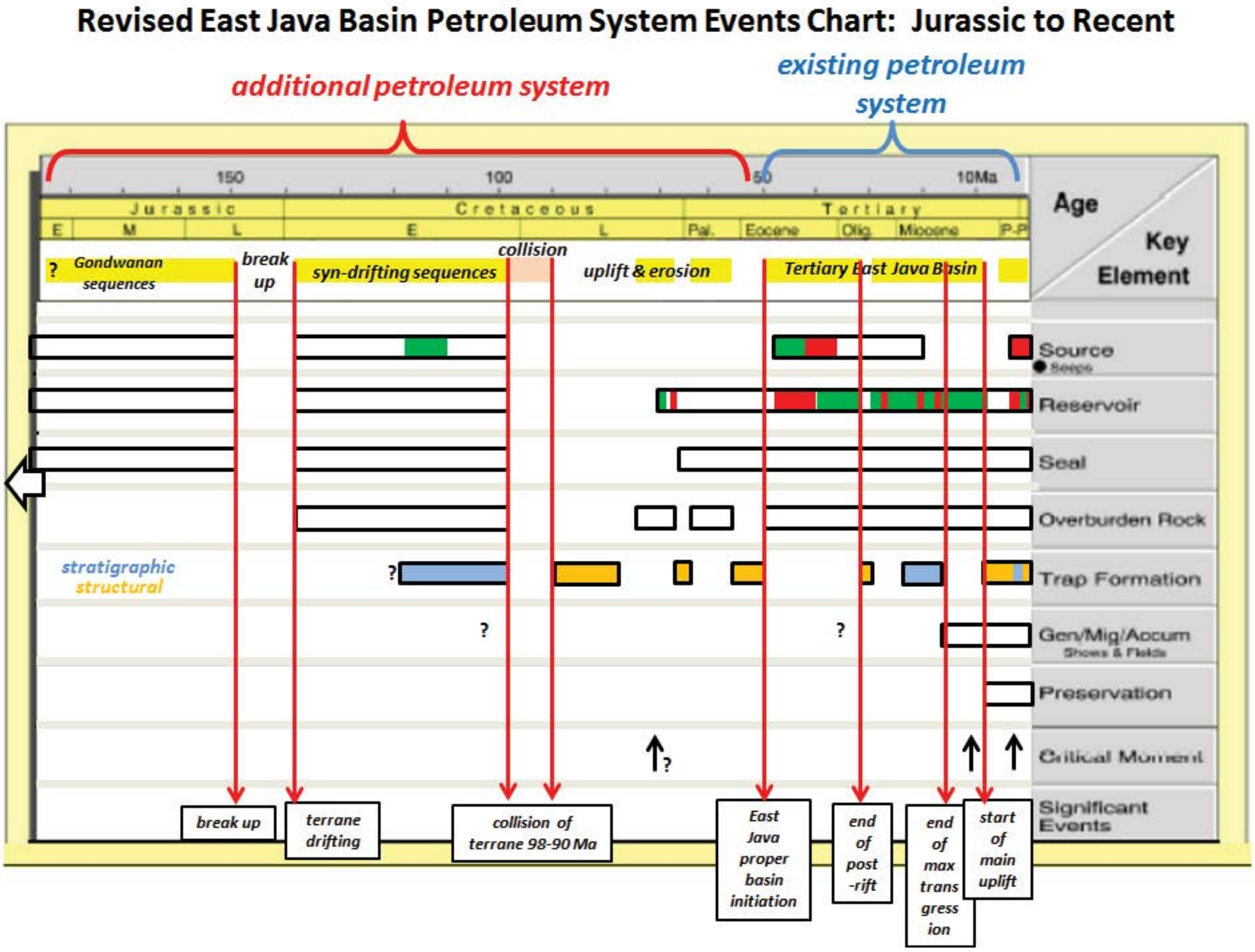

Figure 19 - Revised petroleum system of East Java Basin, incorporating rock elements (source, reservoir, seal, and overburden rocks) Mesozoic in ages. Lower Cretaceous marine shales are proven source rocks generating oils. Trap formation may be stratigraphic during sedimentation or structural inherit the deformation at the original area, or newly formed traps following the collision of microcontinents. Generation of petroleum from Lower Cretaceous shales was at Miocene time, meaning that generation from older sources will be earlier. The chart may also bring Paleozoic sequences if they were deposited.