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THE POWER OF OIL BIOMARKERS FOR REGIONAL TECTONIC STUDIES: HOW THE MOLECULAR FOSSILS IMPACT EXPLORATION VENTURES - CASE STUDIES FROM INDONESIA

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ABSTRACT

Biomarkers are organic chemical compounds whose structure or skeleton of carbon, hydrogen and other elements are formed by living organisms and are sufficiently stable to be recognized in crude oil or in the organic matter of ancient sediments. Biomarkers are also called molecular fossils, indicating formerly living organisms that developed in specific geologic environments.

Development of paleogeographic settings and depositional environments was driven by tectonics. Source rocks with some specific biomarkers were deposited within these depositional environments/ source facies. Oils generated from organic matter of the source rocks contain biomarkers that are specific for depositional environments. Therefore, the oil biomarkers can be used to prove the existence of paleogeographic sites / depositional environments formed by tectonics. This means that oil biomarkers, indirectly, can be used to examine models of tectonics.

Three cases of how oil biomarkers can be used to examine tectonic models are discussed in this paper. Firstly, in Western Indonesia, Paleogene rifted basins of Sumatra that were developed due to stress release of the Sumatran Fault relating to tectonic escape of post-collision India to Eurasia in Eocene time, are examined using oil biomarkers to understand the development of source facies formed duringrifting. Secondly, in Central Indonesia, biomarkers from recently discovered Eocene oils in the deep Makassar Straits and oil seeps in Western Sulawesi onshore are employed to examine the model of the Makassar Straits opening. Finally, in Eastern Indonesia, the Salawati Basin underwent tectonic reversal of its depocenter before and after the advent of the Sorong Fault tectonism in Mio-Pliocene time, and is examined by oil biomarkers from fields charged by Kais/Klasafet sources.

The right understanding of tectonic models is important for determining an appropriate exploration strategy. Therefore, confirmed tectonic models, in this case using biomarker methods, are also important. The area of priority, objectives of exploration drilling, petroleum system analysis and well location selection can be better evaluated based on confirmed tectonic models.

INTRODUCTION

Biological markers or biomarkers are complex organic compounds composed of carbon, hydrogen and other elements. They occur in sediments, rocks and crude oils and show little or no change in structure from their parent organic molecules in living organisms. Biomarkers are molecular fossils, meaning that these compounds originated from formerly living organisms (Peters et al., 2005). Biomarkers are shown as a distribution of molecular concentration measured by gas chromatography (GC), like alkanes and isoprenoids (including pristane and phytane), or gas chromatography-mass spectrometry (GC-MS) like triterpane and sterane. Each pattern of molecular concentration has a specific meaning (Figure 1).

Organic matter accumulating in source sediments possesses distinctive biochemical characteristics inherited from a specific combination between the organisms and the depositional environments where these source sediments were deposited (source or organic facies). Every item of organic matter deposited in a specific depositional environment/source facies developed a specific biomarker (TABLE 1;Hunt, 1996).

The biomarker patterns found in crude oils and source rocks depend both on the type of organic matter incorporated during sedimentation and the subsequent chemical changes that occured during burial in the subsurface. Since these are complex processes that vary considerably from one depositional setting to another, the resulting biomarker distributions are often very different and provide a useful means of fingerprinting geological samples. In other words, biomarkers can be used to

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reveal the source depositional environment (TABLE 1). Accordingly, biomarker patterns can be used to correlate oils with their source formations (Noble, 1991).

Depositional environments vary across different paleogeographic settings. Specific paleogeography from nonmarine to deep marine settings were formed in association with tectonics. Biomarkers preserved in the organic matter of source rocks reflect the paleogeographic setting, and can therefore be used to understand the tectonic setting and tectonic evolution forming the paleogeographic site and the source depositional environment/facies.

Tectonic studies generally have never involved biomarker data to result in tectonic models, causing a gap in model reliability or speculative model. This gap can be improved by analyzing oil biomarkers that migrated from paleogeographic sites or depositional environments that resulted from tectonics.

Accordingly, oil biomarkers can be used to cross-check the tectonic models developed from seismic and well correlation studies.

Three cases of how oil biomarkers can be used to examine tectonic models in Indonesia are discussed, from the Western, Central and Eastern Indonesia areas.

DATA & METHODS

Oil biomarkers from fields or discovery wells are used to determine the source facies that developed in specific paleogeographic depositional environments formed by tectonics. There are tectonic models of the areas under study. These tectonic models did not involve biomarker data to confirm paleogeographic sites formed by tectonics. This study used oil biomarker data of the related areas to determine source facies that are located in paleogeographic sites or source depositional environments formed by tectonics. If the existing tectonic models proposed the development of specific paleogeographic sites and the existence of these sites are confirmed by biomarker data, then the tectonic models are more likely. In this case, oil biomarkers are included as hard data to build a tectonic model.

This study used oil biomarkers since source biomarkers from source sediments within their mature source facies (kitchen) are almost never drilled. When the source sediments were mature and generated oils and the oils migrated to the structures that are drilled, the biomarker of oils can reveal the geologic and geochemical parameters of their sources, including: organic matter, source depositional environment, source lithology, source maturity, source age, and migration history (using geochemical inversion method, Bissada et al., 1992).

Three cases of how oil biomarkers can be used to examine tectonic models are discussed.

Firstly, in Western Indonesia, Paleogene rifted basins of Sumatra that were developed due to stress release of the Sumatran Fault relating to tectonic escape of post-collision India to Eurasia during the Eocene are examined using oil biomarkers to understand the development of source facies formed by rifting

In Central Indonesia, biomarkers from recently discovered Eocene oils in the deep Makassar Straits, along with oil seeps onshore Western Sulawesi are employed to examine the model of the Makassar Straits opening.

In Eastern Indonesia, the Salawati Basin that has been modeled underwent tectonic reversal of its depocenter before and after the advent of the Sorong Fault tectonism in Mio-Pliocene time, and is examined by oil biomarkers from fields charged by Kais/Klasafet sources.

RESULTS & DISCUSSIONS

Role of Biomarkers in Examining Paleogene Rifted Grabens/Basins of Sumatra

a. Formation of Paleogene rifted grabens of Sumatra

The India-Asia plate collision during the Eocene is widely accepted to be the major controlling mechanism for rift-basin development throughout the Southeast Asia region during the Paleogene (Daly et al., 1987; Hall and Morley, 2004), including Sumatra. They considered that the major effect of the India and Eurasia collision was to induce clockwise rotation of Indochina, extension along the Sumatra margin and, presumably, the development of rift basins of South East Asia by a mechanism of post collision tectonic escape (Figure 2). The Paleogene tectonic setting of these basins will affect the basin’s paleogeography which is important for its depositional environments.

The Paleogene time is marked by deposition of a syn-rift sedimentary package in a continental to marine setting. Although the Paleogene grabens and half grabens varied in depth and rate of subsidence, which in detail affected the depositional environment and type of sediment, the stratigraphic successions are remarkably similar. In terms of stratigraphic evolution, the rifting phase can be divided into three major phases, which are: early, middle and late phases of rifting (see stratigraphic column on Figure 2 - Sudarmono et al., 1997).

The early-phase deposits of the Paleogene rift basins of Sumatra are predominantly non-marine, comprising volcaniclastics, fluviatile, alluvial-fan and shallow and deep lacustrine freshwater deposits (Figure 2, stratigraphic column). During the middle phase of rifting, the depositional environment was commonly characterized by deep, broad lakes as earlier, smaller and separated lakes, which developed during the early-rift phase, coalesced as the rate of subsidence exceeded the rate of sedimentation. These broad and deep lakes at the depocenters tended to be restricted from large terrigeneous input and had low relief vegetated areas, which in humid climates are favorable sites for development of organic-rich lacustrine source facies. At the late stage of rifting, lakes commonly were shallower (Sudarmono et al., 1997) and deposition was dominated by coarse clastic fluvio-deltaic processes. Large and shallow embayments with restricted access to marine conditions likely occurred during this period throughout many of the Paleogene basins before the depositional setting gradually changed to fully marine. Marine incursions chronologically were slightly different from basin to basin and were controlled by the rate of subsidence and access and closeness to the open marine system. The western margin of Sundaland (Sumatran Basins) was mostly occupied by marine conditions later than the eastern margin, although the North Sumatra Basin likely was influenced by marine conditions as early as late Eocene. The post-rift phase is coincident with relative sea level rise resulting in a transgressive setting. There was a shift in provenance from sediment derived from a mixed metamorphic-granitic terrain of local basement highs/horst blocks and volcanic source terrain during early to middle rift-phase to a progressively more mature granitic/quartzose basement derived from the Sunda craton during the end of rifting to the post-rift period.

Paleogene source facies of the Sundaland basins comprises sources from depositional phases of early phase of rifting, middle and late phases as well as post-rift phases. Paleogene source rocks that have generated hydrocarbons in Sumatran basins vary from organic-rich lacustrine facies of early and middle-phases of rifting, to carbonaceous shales and coals of fluvio-deltaic, paralic and marginal marine of late phases of rifting and post-rifting and marine facies of post-rifting (Satyana and Purwaningsih, 2013).

b. Confirmation from oil biomarkers from the rift grabens of Sumatra

The presence of Paleogene riftbasins in Sumatra – as seen on 2D and 3D seismic underpins the tectonic model which can be examined by biomarkers of oils generated from source rocks deposited within the rifted grabens. There are almost no wells drilled within these grabens that penetrated the source rocks therefore the hard data that show the presence of source rocks within these rifted grabens are only the biomarkers of oils generated from these source rocks, except for outcrops of the source rocks, if any (Carnell and Butterworth, 1997). Well based- biostratigraphic data cannot prove either the presence of rifted grabens since most of the wells are located out of the rifted grabens and do not penetrate rifting sediments.

South Sumatra Basin. Fluvio-deltaic source facies dominates the oils of this basin (Figure 3). Bicadinane and oleanane, deriving from angiosperm resins of some SE Asian higher land plants exist in oils. Tricyclic terpane is minimal, showing nonmarine or non-lacustrine algal association for these oils. Sterane distribution with dominant C_{29} show significant terrestrial/fluvio-deltaic input. Fluviodeltaic oils have a very characteristic m/z 217 scan usually containing only C_{29} steranes and diasteranes. The dominant compounds on the scan are C_{30} resin derived cyclic alkanes, which are also present on the m/z 191 triterpane scan. Robinson (1987) compared triterpane and sterane distributions of fluvio-deltaic oils from the South Sumatra, Kutei and Tarakan Basins, whichshow little variation between them, suggesting the organic facies and original higher plant input is similar in all these basins, although the source age of South Sumatra (Paleogene Talang Akar) is different with those Neogene sources from the Kutei and Tarakan Basins. GC of Bentayan oil may indicate the presence of shallow lacustrine source facies in this basin with enriched C_{23}-C_{29} and Pr/Ph < 3.0. Proven sources of the South Sumatra Basin are believed to be the Early Oligocene synrift Lemat shales and the Late Oligocene late synrift-early postrift Talang

Akar coals and coaly shales (Satyana and Purwaningsih, 2012)

Central Sumatra Basin. Lacustrine facies dominates the source rocks of this basin (Figure 4). The characteristics are bimodal to broad n-alkane distribution due to input of C_{15}-C_{19} and C_{23}-C_{33} n-alkanes from non-marine algae, low Pr/Ph ratios < 3.0 and have low Pristane/nC_{17} ratios. Lacustrine oils are typically high wax (C_{31}/C_{19} > 0.4). Deep lacustrine sourced-oils tend to have simple triterpane distributions containing only pentacyclic 17α hopanes from C_{27}-C_{35} plus moretanes and little else. The Tm/Ts ratio, which is maturity and organic facies influenced, is low and enriched in tricyclic terpanes. Steranes relative to hopanes tend to be in low concentrations. Deep lacustrine oils usually contain the full range of C_{27}-C_{29} steranes and diasteranes, albeit in very low concentrations, and usually have a roughly equal concentration of C_{27} and C_{29} steranes. However, a characteristic of deep lacustrine oils in Indonesia is the unusually high concentration of C_{30} 4-methyl steranes in many of the oils. These can be identified from m/z 231, 414 scans and are also present on the m/z 217 scan (Robinson, 1987). These compounds are believed to be derived from dinoflagellates, but are also probably derived from non-marine planktonic algae. The resence of high Pr/Ph (> 6.0, MSCQ-1 oil) shows the presence of a fluvio-deltaic source in addition to the predominant lacustrine shales. The Oligocene synrift Pematang shales are the source rocks of the Central Sumatra Basin (Robinson, 1987; Satyana and Purwaningsih, 2012).

North Sumatra Basin. Different compared to other basins encircling Sundaland, North Sumatra oils show predominating marine oils as indicated by their GC alkane, triterpane and sterane scans (Figure 5). GC scans show decreasing concentration of higher molecular weight n-alkanes (low wax content), Pr/Ph < 3.0, Pr/ C_{17} ratio < 1.0, low wax (< 0.4 C_{13}/C_{19}). Triterpane scans have relatively simple hopane and moretane distributions, Tm/Ts values range from 3.0 to 1.0. The presence of 18α oleanane, indicating transportation of resistant higher plant resins into the marine basin and not indicative of a terrestrial source for the oil. It is noticeable that other C_{30} resin derived compounds, commonly found in association with oleanane, are absent or in very low concentrations. Marine oils of North Sumatra are also indicated by relatively high concentrations of tricyclic terpanes. Based on steranes, isomer C_{27} dominates the distribution, indicating marine facies. The abundance of C_{27} steranes is often associated with an algal input. Pentacyclic terpane of TJ-1 oil also shows C_{30} hopane/C_{29} norhopane ratio < 1.0, indicating a carbonate source in addition to marine shales as indicated by C_{30} hopane/C_{29} norhopane ratio >1.0 (BM-1 and NSB-H1 oils). Subroto et al. (1992) investigated this matter and considered that the TJ-1 crude oil is most likely to have been derived from a carbonate-rich source rock with similar characteristics to the sediments of the Early Miocene Peutu/Arun Formation at Rayeu-B1. The maturity of the Peutu Formation also appears to be sufficient to have generated the TJ-1 crude oil. While the BM-1 and NSB-H1 have biomarker characteristics clearly relating them to similar source and depositional conditions to the shale sample of the Mid-Miocene upper Baong Formation at Rayeu-B1, the maturity of these formations for crude oil formation is questionable. If these formations have not reached sufficient maturity in the basin, then deeper and more mature sources with similar source and depositional conditions must be sought as a source of these crude oils. Such a source may be the Oligocene Bampo Formation which comprises mainly shales deposited in shallow to deep marine conditions.

Based on oil biomarkers, the tectonic model showing the formation of the Paleogene rifted grabens in Sumatran basins developing various environments and facies for source sediments to be deposited, is proven. The source rocks of the rifted grabens of Sumatran basins developed in various source facies, including: organic-rich lacustrine facies of early and middle-phases of rifting – dominant in the Central Sumatra Basin: carbonaceous shales and coals of fluvio-deltaic (dominant in South Sumatra Basin);and paralic to marginal marine of late phases of rifting and post-rifting and marine facies of post-rifting (North Sumatra Basin) (Satyana and Purwaningsih, 2013).

Role of Biomarkers in Confirming Paleogene Opening of the Makassar Straits

a. Opening of the Makassar Straits

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 of 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. To the east of the Makassar Straits is the West Sulawesi onshore area which is an important area to understand the evolution of the Makassar Straits. Numerus oil and gas seeps have been reported from this area. (Figure 6).

While the Paleogene history for the opening of the Makassar Straits is commonly agreed, the mechanism for the opening of the Makassar Straits and nature of the basement underlying the straits have been the subject of considerable scientific debate. 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, the deep water areas of the Makassar Straits were intensively explored. Speculative seismic surveys were acquired and working blocks were awarded to oil companies. They performed exploration studies, acquired detailed 2D-3D seismic data and other geophysical-geological data. Many exploration wells were drilled. Satyana et al. (2012) summarized these activities and reported the exploration results and its implications to the geological knowledge of the Makassar Straits. Based on new data acquired during recent exploration activities in this area, Satyana (2015) proposed a new tectonic model of the opening of the Makassar Straits.

Rifting of the Makassar Straits is clearly shown on seismic sections (Figure 7). The undisputed graben and half grabens seen in parts of the straits mapped by Nur'aini et al. (2005) indicate extended continental crust. Extension began in the Early-Middle Eocene and formed graben and half graben above which is an important unconformity of probable Late Eocene age. The unconformity marks the top of the 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 the 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 the broad Paternoster Shelf could cause the orientation of rifting in this area being different with that of North Makassar Basin. The opening of the South Makassar Basin could be related to rifting of the basement in the East Java Basin to the southwest, which is 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, 1982). The formation of the basin started with rifting in the Lower-Middle Eocene or probably earlier and continued until the Lower Miocene. Multichannel reflection seismic data from the basin indicates 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, forming oceanic crust, 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 is proved by Rangkong-1 and Kaluku-1 wells penetrating the basement as discussed in the recent paper by Satyana (2015).

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 thinned continental crust, proposed a part of Gondwanan Paternoster-West Sulawesi microcontinent Satyana (2015), 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.

Rifting of North and South Makassar Straits ceased by the end of Lower Miocene (Situmorang, 1982) and failed to develop further into sea-floor spreading. The cause was collisions of microcontinents to the east of Sulawesi in Neogene time, firstly by collision of the Buton-Tukang Besi microcontinent in Early-Late Miocene and secondly by collision of the 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 the 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 is 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 the Mahakam delta prograded east since the Early Miocene, while folding and thrusting of western Sulawesi migrated westward since the Early Pliocene.

b. Confirmation from oil biomarkers for Makassar Straits opening

The opening of the Makassar Straits can be confirmed indirectly by oil biomarkers from discovery well Kaluku-1 (ConocoPhillips Kuma, 2011 – Satyana et al., 2012) drilled on the rifted horst of the Makassar Straits, and biomarkers of oil seeps onshore West Sulawesi. It is modeled tectonically that the source facies of the onshore West Sulawesi oil seeps will be terrestrial-fluviodeltaic, whereas the source facies of the rifted structures of the Makassar Straits will be lacustrine due to the presence of rifted grabens. Both of the source rocks are Eocene in ages. This is based on the evolution of the Makassar Straits opening which started as a continental rifting (forming lacustrine) in between terrestrial areas of Eastern Kalimantan and Western Sulawesi.

The oils recovered by the Kaluku-1 well from Eocene reservoirs of the rifted horst are highly waxy and solid at room temperature. A recent paper by Satyana (2015) discussed in detail the oil geochemistry. The laboratory analysis shows an API of 25.5-29.6 at 60º F and pour point of 110-113º F from depth of 15,752 ft. oil sample, its sulfur and wax contents are 0.060-0.102 and 17.23-21.09 % wt., respectively. The waxy nature of the oil suggests a lacustrine source.

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 2.25-2.48) This suggests derivation from a fresh shallow lacustrine facies. GC-MS results show that the oil was generated from a mature source rock deposited within a terrestrial environment with algal input to shallow lacustrine (Figure 8).

Biomarkers present in these oils have been analyzed by computerized GCMS performed on saturate and aromatic fractions. Triterpanes including hopanes (m/z 191) fragmentograms displays relatively simple distributions of bacterially-derived 17αβ (H)-hopanes where C_{30} hopane is relatively high to C_{29} norhopane, showing shaly source rocks. 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 relative to the C_{23} tricyclic compound. This indicates a lacustrine algal origin. The 18α (H)-Oleanane peak is relatively very low in both samples and suggests limited terrestrial input or far from deltaic oleanane source. Steranes (m/z 217) distributions for both oil samples show a full suite of normal steranes with the $C_{27}\alpha\alpha\alpha(R)$ forms less abundant (28.17 % -37.87 %) relative to the $C_{29}\alpha\alpha\alpha(R)$ steranes (42.65-59.92 %). This implies a significant contribution of terrestrially-derived 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". 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 the 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. Organic materials of the lacustrine source facies are fresh-water algae, and this should mark continental facies, not oceanic facies therefore it is concluded that there is no oceanic crust underlying the Makassar Straits.

The West Sulawesi onshore area geologically shares a similar tectonostratigraphic setting with the sedimentary basins of Sundaland. West Sulawesi is the easternmost margin of the Sundaland that drifted away from the Sundaland by opening of the Makassar Straits. There are numerous oil and gas seeps in onshore West and South Sulawesi and have been characterized geochemically (Figure 9).

In the Kalosi area, all of the oils were generated within the oil window (Ro 0.60% to 0.90%) (Coffield et al, 1993). Geochemical analysis of the oils indicate they are paraffinic, low sulfur, moderately low wax to waxy oils with API gravities (where not biodegraded) of 35° to 40°. Except for maturity differences, a good correlation exists between the oils and the Eocene coals and carbonaceous claystones of the Toraja Formation based on GC, GC-MS and carbon isotope data. All of the Eocene coals have high pristane and phytane ratios (6.0-15.20) similar to or greater than the oils.

During pyrolysis-GC experiments, the coals generated similar waxy hydrocarbon products at maturity. The carbon isotopes for the aromatic fractions are very similar (within 1 per mil) while the tricyclic, tetracyclic and pentacyclic terpane biomarker distributions are the same. The bicadinanes and steranes also both show good correlations. Coals and carbonaceous claystones deposited in fluviodeltaic depositional environments are present in the Kalosi area in the upper portion of the Toraja Formation (middle-late Eocene) and are considered to be the primary source rocks of the oil and gas seeps. The rocks contain Type II/III terrestrially influenced kerogens and have TOC values in the range 31% to 81% and HI values ranging from 158 to 578.

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

The Eocene coal samples have been characterized and show similar GC alkane distribution. GCMS m/z 191 triterpane shows minimum tricyclic terpane, low ratio of 29-norhopane and 30-hopane and abundant oleanane. GCMS m/z 217 sterane shows a dominant C29 distribution and abundant bicadinane. These characteristics show that West Sulawesi oil seeps were sourced by terrestrial coaly fluvio-deltaic shales. Sources of these seeps are similar in nature with Paleogene coals and coaly shales of South Sumatra, West Java, East Java and Barito Basins.

Characteristics that Eocene oils in the rifted horst of the Makassar Straits are sourced from a lacustrine facies, whereas the Eocene oil seeps of onshore West Sulawesi are terrestrial fluviodeltaic facies that shows that the history of the Makassar Strait rifting started in the middle of the present Makassar Straits as continental rifted graben forming a lacustrine depocentre where source sediments were deposited with organic matters that came from fresh water algae (lacustrine). On the areas of nonrifted continent – present Western Sulawesi and Eastern Kalimantan (in this case Barito Basin), the environment/facies developed as terrestrial fluvio-deltaic facies as shown by biomarkers of oils from West Sulawesi oil seeps and oil fields of the Barito Basin in Southeast Kalimantan (Satyana and Purwaningsih, 2013).

The oil biomarkers also show that the West Sulawesi onshore oils are more mature than those of West Sulawesi offshore due to different tectonic regimes (Figure 10). Different tectonic regimes between onshore and offshore West Sulawesi are also supported by oil biomarkers. In West Sulawesi offshore, one should explore Paleogene (especially Eocene) targets to find oil that is more possible due to shallow targets (Neogene) that have never been charged by Palogene sources because the presence of seal detachment in between Paleogene and Neogene sections (thin-skinned tectonics). Exploring Neogene objectives has proved to be failure in this area (Satyana et al., 2012; Satyana, 2015). The Neogene objectives of West Sulawesi Offshore are a failure due to: (1) presence of regional and very thick shale decollement/detachment below the thin-skinned structures that may act as a barrier to block migration from Paleogene sources to Neogene reservoirs, (2) lack of organic-rich source rocks in the Neogene section due to the volcanic-clastic nature of the sedimentary sections and (3) lack of maturity due to shallow burial depths and recent deformation.

Toward onshore Western Sulawesi, offshore thin-skinned structures changed in structural style to become thick-skinned structures. Faults connect the Paleogene sources to Neogene reservoirs and become migration conduits as proved by oil seeps in the Neogene section that are geochemically characterized and show Eocene sources. In the West Sulawesi onshore, Neogene objectives were charged by Paleogene sources due to the absence of seal detachment in between them (thick-skinned tectonics).

Role of Biomarkers in Confirming Reversal of the Salawati Basin, Eastern Indonesia

a. Reversal of the Salawati Basin

The Salawati Basin is an east-west trending asymmetric foreland basin located on the northern margin of the Indo-Australian Plate. The basin is presently bounded to the north and west by the deformed zone of the left-lateral Sorong Fault separating the basin with the Caroline-Philippine oceanic plate. The basin is terminated to the south and east by uplifted Miocene carbonates of the Misool-Onin Geanticline and the Ayamaru Platform respectively (Figure 11). The Salawati Basin records the stratigraphic and tectonic history from Paleozoic time to Recent.

The main structural framework of the Salawati Basin is the Sorong Fault, terminating the basin to the north. This is a major left - lateral fault that has been active since the mid- Pliocene. The Sorong Fault strongly controlled the geology of the basin during the late Pliocene. Regional studies from 1997 to 2000 (Satyana et al., 2000; Satyana and Setiawan, 2001; Satyana, 2001; Satyana, 2003 and Satyana and Herawati, 2011) on basin evolution, structure, geochemistry, Kais paleogeography and carbonate sedimentology concluded that the Salawati Basin underwent a polarity reversal from tilting southward (southern depocenter) during the Paleozoic to early Pliocene, to tilting northward (northern depocenter) since the late Pliocene (Figures 12 and 13).

The original interpretation of the evolution of the Salawati Basin was discussed by Gibson-Robinson and Soedirdja (1986), detailing the transgressive development of Miocene Kais reefs. They did not recognise the reversal of the basin's polarity. The Salawati Basin setting during the Miocene was determined by Gibson-Robinson and Soedirdja (1986) as the site of carbonate deposition in an embayment that was probably open to the northwest. In the southern and eastern parts of the basin, shallow carbonates were deposited, apparently continuously during Miocene time. In the central part of the basin, these shallow-water carbonates are absent and the early and middle Miocene section consists of relatively deep-water limestones, containing a fauna of planktonic foraminifera and interbedded open-marine calcareous shales. These deposits form the Klamogun Formation and are overlain by middle to late Miocene shales and thin limestones of the Klasafet Formation. Between these two depositional areas a third province developed, probably beginning during middle Miocene time, as renewed transgression took place. In this area, termed the shelf margin, a series of pinnacle reefs and carbonate banks developed in the Kais Formation, and it is these that are productive oilfields. Based on this interpretation, it is clear that the depocenter of the Salawati Basin during the Kais carbonate deposition was to the north, with shelf margin in the middle and shallow water to the south. The Kais Platform passes basinward to the north into deeper marine limestones of the Klamogun Formation and shales of the lower Klasafet. Over the platform area, shoals probably developed which became sites for later reef growth. At the end of the Kais platform stage there was a broad division into an open marine basin to the north and a shallow shelf area to the south.

Satyana et al. (2000), Satyana (2001, 2003) and Satyana and Herawati (2011) proposed a new tectonic evolution of the Salawati Basin. The model argued that the advent of Sorong tectonism to the Salawati Basin caused the basin's polarity (basin's platform and depocenter) reversal before and after mid-Pliocene time. The fault was responsible for the reversal of the basin's polarity – forming the present basin's depocenter to the north-northwest and uplifting of the south-east-northeastern parts of the basin. Seismic and well data show that before the period of the Sorong Fault tectonism, the Salawati Basin had dipped to the south. All strata from the Late Paleozoic to Early Pliocene thicken to the south indicating the presence of the basin's depocenter somewhere in the south (Figures 12, 13). During the Kais carbonate deposition in Miocene time this condition remained the same. This new interpretation was different with that of Gibson-Robinson and Soedirdja (1986)'s interpretation which show a northern depocenter during the Kais carbonate deposition. This change of interpretation causes northern deep water carbonate of Stage-1 mentioned by Gibson-Robinson and Soedirdja (1986) is reinterpreted as lagoonal carbonate deposition of Stage-1 (Satyana, 2003). Satyana et al. (2000), Satyana (2001, 2003) interpreted that there was a northern landmass during the Miocene (FIGURE 13). The sea inundated almost all of the emergent areas of the Salawati basement including the northern landmass. The carbonates were deposited during progressive northward transgression and thicken to the south from approximately 200 feet in the northern area (WIR-1 well) to 4000 feet in the southern area (Walio-69 well). The onset of Kais carbonate sedimentation in the Salawati Basin took place in the Oligo-Miocene, based on the presence of Lithothamnium/ Mesophyllum type red algae and Amphistegina in WIR-1A. Fringing reefs of Klagagi- Klalin-Arar Complex developed to the south of the Arar High/Landmass. An extensive carbonate bank, the Walio Carbonate Bank, developed in the south in an area free of siliciclastic input forming a barrier to the southern open sea. A broad lagoonal facies developed between the carbonate bank and the landmass. Marly carbonates were deposited within the lagoonal area during the Kais time and overlying Klasafet Formation. Low-relief reefal carbonates grew in various parts of the lagoon (e.g. the Matoa, Salawati-O, SW "O", Amuk Fields.).

By the advent of Sorong tectonism to the north of the Salawati Basin, the basin compensated isostatically in the way of reversing its polarity (Figure 13). In the upper early Pliocene, the basin started to subside to the north-northwest and this terminated the sedimentation of carbonates dominating since the Early Tertiary. Reversely, the southern depocenter was uplifted comprising mainly of Kais-Klasafet carbonates and mudstones. The eastern and northeastern areas of the basin were also uplifted to compensate for the new depocenter in the northwestern and western parts of the basin. The uplifted mass became the provenances for the lower Klasaman siliciclastic sediments mainly comprising shales, siltstones, bioclasts and limestones. The Salawati Basin gained its present asymmetric geometry at this time. The basin was terminated to the south and east by the uplifted mass of Misool-Onin Geanticline and Ayamaru Platform comprising Kais carbonates. The basin subsided to the north, northwest and west, forming the present kitchen sourced by Kais and Klasafet carbonates, marls and shales.

As discussed above, based on the interpretation of Gibson-Robinson and Soedirdja (1986), the source facies of Kais/Klamogun and Klasafet in the kitchen should be deep water – open marine carbonates. Whereas, based on the interpretation of Satyana (2003) the source facies should be lagoonal sediments.

b. Confirmation from oil biomarkers for Salawati Basin reversal

Updated geochemistry (hydrocarbon sources) of the Salawati Basin was discussed by Satyana et al. (2000) and Satyana and Wahyudin (2000).

Source identification was obtained by geochemistry of analyzed oils through oil to source rock correlation. The geochemical characteristics of Salawati oils show distinctive features listed below (Figure 14):

- Moderate content of sulphur aromatics suggesta marine affinity because the sulfur is generally formed by microbial sulfate reduction of sea water and is normally associated with carbonate muds.
- Heavy carbon-13 isotope ratio mostly -19 ‰ to - 22 ‰, suggests a dominant contribution by highly anoxic algae, and is organically very rich.
- Presence of the Tertiary higher plant biomarker oleanane indicates some fresh water run-off from terrestrial angiosperms from delta vegetation, and a Tertiary aged source sediments
- Pristane to phytane ratios are generally below 2.0 indicating organic-rich anoxic carbonate sequences.

Integration of the above characteristics provide a specific model for the type of source rock for Salawati Basin oils. Source rocks should be: Tertiary in age, organically very rich, have a significant marine influence, contain dominantly marine algal kerogens, have received minor terrestrial run-off, carbonate (lime mudstone) in part and in most cases have been deposited in an anoxic lagoonal (brackish water) environment. These characteristics point to Kais and Klasafet shales and carbonates as the source rocks for Salawati oils, deposited in the anoxic to suboxic lagoon (FIGURE 15). The richest of the analyzed Kais and Klasafet source rocks have been analyzed for biomarkers and carbon isotope ratio at various times. This data shows significant correlations with existing produced oil. Biomarkers and carbon isotope data illustrates the compatibility of the Kais/Klasafet source rock to the Salawati oils.

Oil biomarkers support new interpretation by Satyana (2003). Biomarker data shows that the sources are rich, anoxic, with strong marine influence and less terrestrial input, this condition is fulfilled by lagoonal paleogeographic sites, not a deep water open marine setting of Kais/Klamogun/Klasafet sources as interpreted by Gibson-Robinson and Soedirdja (1986). Deep water and open marine source facies will be lean in organic richness, oxic and have almost no terrestrial input. Based on oil geochemistry, the reversal of the Salawati Basin occurred which subsided once Kais/Klasafet lagoonal source materials (Figure 15) to presently like a deep-water open marine carbonates.

Petroleum Exploration Implications

The right understanding of the regional geology will result in the correct steps of exploration. An exploration strategy should be based on the geologic and tectonic setting of the exploration area, such as determining the area of priority, objectives of exploration drilling, petroleum system analysis and well location selection. Knowledge of the geologic and tectonic setting should be gained first. The Tectonic model proposed should be examined so that it can be referred to for building the exploration strategy. This study shows how to examine tectonic models utilising biomarkers.

In the case of Paleogene rifted basins in Sumatra, oil biomarkers in South Sumatra, Central Sumatra, and North Sumatra prove the existing tectonic model of the presence of rifted kitchens during the Paleogene. Oil biomarkers from fields charged by generated oils from these kitchen show a variation of source facies from deep lacustrine, shallow lacustrine, fluvio deltaic, marginal marine to marine. This input will be significant when exploration objectives target the synrift reservoirs. Petroleum system analysis and well location selection for exploring syn-rift objectives will be better evaluated if this is known.

On the case of the Makassar Straits opening, oil biomarkers from the Kaluku-1 discovery well in the present West Sulawesi offshore area and oil seeps in West Sulawesi onshore prove the tectonic model of the Makassar Straits opening by continental rifting. The oil biomarkers showed that the Paleogene opening formed the rifted grabens in offshore area where lacustrine source facies developed, whereas fluvio-deltaic terrestrial source facies developed in the West Sulawesi onshore. The oil biomarkers also show that the West Sulawesi onshore oils are more mature than those of West Sulawesi offshore due to a different structural style. The different structural style between onshore and offshore West Sulawesi is also supported by oil biomarkers. In West Sulawesi offshore, one should explore the Paleogene (especially Eocene) targets to find more possible oil due to shallow targets (Neogene) never having been charged by Palogene sources because the presence of seal detachment in between Paleogene and Neogene sections (thin-skinned tectonics). In West Sulawesi onshore, Neogene objectives were charged by Paleogene sources due to the absence of seal detachment in between them (thick-skinned tectonics).

In the case of the Salawati Basin reversal, for the Miocene Kais carbonates, the northern area of the basin which was based on old interpretation to be deep-water carbonates, no exploration was carried out due to possibly poor reservoir quality. New reinterpretation shows that the carbonates were lagoonal carbonates, subsiding later in geologic history due to the basin’s depocenter reversal by the advent of the the Sorong Fault. Oil biomarkers of oils generated from these carbonates show the lagoonal source facies, hence proving the reversal of the basin’s depocenter. These lagoonal carbonates, marls and shales of Kais and Klasafet Formations are proven source rocks and in the area of the lagoon there were developments of low-relief carbonates build ups above or within the carbonate platform. Exploration on these structures show good prospectivity of Kais lagoonal carbonates which previously was not explored due to being erroneously interpreted as deep-water carbonates.

CONCLUSIONS

Development of paleogeographic settings and depositional environments are driven by tectonics. Source rocks with some specific biomarkers were deposited within these depositional environments/ source facies. Oils generated from the organic matter of the source rocks contain biomarkers that are specified for specific depositional environments. The oil biomarkers, therefore, can be used to prove the existence of paleogeographic sites / depositional environments formed by tectonics. This means that oil biomarkers, indirectly, can be used to examine models of tectonics.

Three areas are discussed to show how oil biomarkers can be used to examine models of tectonics. (1) Tectonic model of Paleogene rifted basins of Sumatra confirmed its existence by oil biomarkers from fields charged by oils from the rifted kitchens. (2) Tectonic model of Paleogene Makassar Straits opening confirmed its existence by oil biomarkers from oils discovered on Eocene sands of the rifted horst of the Makassar Straits and oil seeps from West Sulawesi onshore. (3) Tectonic model of Mio-Pliocene Salawati Basin depocenter reversal due to Sorong Fault tectonism is confirmed by oil biomarkers from the Kais/Klasafet carbonate source rocks showing lagoonal source facies developing before the carbonate platform subsided by basin reversal.

The right understanding of the regional geology and the tectonic model is important for determining exploration strategy. Therefore, a confirmed tectonic model, in this case using the biomarker method, is also important. The area of priority, objectives of exploration drilling, petroleum system analysis and well location selection can be better evaluated based on the confirmed tectonic model.

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REFERENCES

Bissada, K.K., Elrod, L.W., Darnell, L.M., Szymczyk, H.M., and Trostle, J.L., 1992, Geochemical inversion – a modern approach to inferring source-rock identity from characteristics of accumulated oil and gas, Proceedings Indonesian Petroleum Association, 21st Annual Convention, Jakarta, 165-200.

Coffield, D.Q. Bergman, S.C. Garrard, R.A., Guritno, N., Robinson, N.M. & Talbot, J. 1993, Tectonic and stratigraphic evolution of the Kalosi PSC area and associated development of a Tertiary petroleum system, South Sulawesi, Indonesia, Proceedings Indonesian Petroleum Association, 22nd Annual Convention, 679–706.

Daly, M.C., Hooper, B.G.D, and Smith, D.G., 1987, Tertiary plate tectonics and basin evolution in Indonesia, Proceedings Indonesian Petroleum Association, 16th Annual Convention, Jakarta, 399-428.

Gibson-Robinson, C. and Soedirdja, H., 1986, Transgressive development of Miocene reefs, Salawati Basin, Irian Jaya, Proceedings Indonesian Petroleum Association, 15th Annual Convention, 377-403.

Hall, R. and Morley, C.K., 2004, Sundaland Basins, in: Clift, P. Wang, P. Kuhnt, W. and Hayes, D.E., (eds), Continent–Ocean Interactions within the East Asian Marginal Seas, American Geophysical Union (AGU) Monograph, 149, 55–85.

Hunt, J.M., 1996, Petroleum Geochemistry and Geology, 2nd Ed., W.H. Freeman and Company, New York.

Noble, R.A., 1991, Geochemical techniques is relation to organic matter, in Merril, R.K. ed., Source and Migration Processes and Evaluation Techniques, Treatise of Petroleum Geology-Handbook of Petroleum Geology, The American Association of Petroleum Geologists, Tulsa, 97-102.

Nur'Aini, S. Hall, R. & Elders, C.F. 2005, Basement architecture and sedimentary fills of the North Makassar Straits basin, Proceedings Indonesian Petroleum Association, 30th Annual Convention, 483–497.

Peters, K.E. and Moldowan, J.M., 1993, The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments, Prentice-Hall, Inc., Englewood Cliffs.

Peters, K.E., Walters, C.C. and Moldowan, J.M., 2005, The Biomarker Guide, Second Edition, Vol. I & II, Cambridge University Press, Cambridge.

Robinson, K.M., 1987, An overview of source rocks and oils in Indonesia, Proceedings Indonesian Petroleum Association, 16th Annual Convention, 97-122.

Satyana, A.H. and Wahyudin, M., 2000, Meteoric Water Flushing and Microbial Alteration of Klamono and Linda Oils, Salawati Basin, Eastern Indonesia: Geochemical Constraints, Origin, and Regional Implications, Proceedings Indonesian Association of Geologists (IAGI), 29th Annual Convention, 71-84.

Satyana, A.H., Salim, Y., and Demarest, J.M., 2000, Significance of Focused Hydrocarbon Migration in the Salawati Basin: Controls of Faults and Structural Noses, Proceedings Indonesian Petroleum Association (IPA), 27th Annual Convention, Jakarta, 513-530.

Satyana, A.H., 2001, Dynamic Response of the Salawati Basin, Eastern Indonesia to the Sorong Fault Tectonism: Example of Inter-Plate Deformation: Proceedings Indonesian Association of Geologists (IAGI) 30th Annual Convention and Geosea 10th Regional Congress, 288-291.

Satyana, A.H. and Setiawan, I., 2001, Origin of Pliocene deep-water sedimentation in Salawati Basin, Eastern Indonesia: deposition in inverted basin and exploration implications: Proceedings Indonesian Sedimentologists Forum, 2nd Regional Seminar on Deep-Water Sedimentation of Southeast Asia, Jakarta, 53-65.

Satyana, A.H., 2003, Re-evaluation the sedimentology and evolution of the Kais carbonate platform, Salawati Basin, Eastern Indonesia: exploration significance, Proceedings of Indonesian Petroleum Association, 29th Annual Convention, 185-206.

Satyana, A.H. & Purwaningsih, M.E.M, 2011, Collision of Micro-continents with Eastern

Sulawesi: Records from Uplifted Reef Terraces and Proven-Potential Petroleum Plays, Proceedings Indonesian Petroleum Association (CD), 35th Annual Convention, Jakarta.

Satyana, A.H. and Herawati, N., 2011, Sorong Fault Tectonism and Detachment of Salawati Island: Implications for Petroleum Generation and Migration in Salawati Basin, Bird's Head of Papua, Proceedings Indonesian Petroleum Association (CD), 35th Annu. Conv., Jakarta.

Satyana, A.H., Damayanti, S.& Armandita, C., 2012, Tectonics, stratigraphy and geochemistry of the Makassar Straits: recent updates of exploring West Sulawesi offshore, opportunities and risks, Proceedings Indonesian Petroleum Association (CD), 36th Annual Convention, Jakarta.

Satyana, A.H., Purwaningsih, M.E.M, 2013, Variability of Paleogene Source Facies of Circum-Sundaland basins, Western Indonesia: Tectonic, Sedimentary and Geochemical Constraints – Implications for Oil Characteristics: Petroleum Implications, Proceedings Indonesian Petroleum Association (CD), 37th Annu. Conv., Jakarta.

Satyana, A.H., 2015, Rifting History of the Makassar Straits: New Consideration from Well Penetrating the Basement and Oils Discovered in Eocene Section – Implications for Further Exploration of West Sulawesi Offshore, Proceedings Indonesian Petroleum Association (CD), 39th Annu. Conv., Jakarta.

Situmorang, B., 1982, The formation of the Makassar Basin as determined from subsidence curves, Proceedings Indonesian Petroleum Association, 11th Annual Convention, 83-107.

Subroto, E.A., Alexander, R., Pranjoto, U., and Kagi, R.I., 1992, The use of 30-norhopane series, a novel carbonate biomarker, in source rock to crude oil correlation in the north Sumatra Basin, Indonesia, Proceedings Indonesian Petroleum Association, 21st Annual Convention, Jakarta, 145-163.

Sudarmono, Suherman, T., Eza, B., 1997, Paleogene basin development in Sundaland and its role to the petroleum systems in Western Indonesia, in Howes, J.V.C. and Noble, R.A. (eds), Proceedings of the Petroleum Systems of SE Asia and Australasia Conference, May 1977, Indonesian Petroleum Association, Jakarta, 545-560.

TABLE 1

BIOLOGICAL MARKERS (BIOMARKERS) AS SOURCE AND PALEOENVIRONMENTAL INDICATORS (HUNT, 1996).

Biomarker	*C range*	*Indication*
n-alkanes		
CPI>5	C_9–C_{21}	Marine, lacustrine algal source, C_{15}, C_{17}, C_{19} dominant
	C_{25}–C_{37}	Terrestrial plant wax source, C_{27}, C_{29}, C_{31} dominant
CPI<1	C_{12}–C_{24}	Bacterial source: oxic, anoxic, marine, lacustrine
	C_{20}–C_{32}	Saline, anoxic environment: carbonates, evaporites
Acyclic isoprenoids		
Head to tail		
Pristane	C_{19}	Chlorophyll, α-tocopherol, oxic, suboxic environments
Phytane	C_{20}	Chlorophyll, phytanylethers of methanogens, anoxic, saline
Head to head	C_{25},C_{30},C_{40}	Archaebacteria, bacterial cell-wall lipids
Botrycoccane	C_{34}	Lacustrine, brackish
Sesquiterpenoids		
Cadalene, eudesmane	C_{15}	Terrestrial plants
Diterpenoids		
Abietane, pimarane, kaurane, retene	C_{19},C_{20}	Higher plant resins
Tricyclic terpanes	C_{19}–C_{45}	Diagenetic products of bacterial and algal cell-wall lipids
Tetracyclic terpanes	C_{24}–C_{27}	Degradation of pentacyclic triterpenoids
Hopanes	C_{27}–C_{40}	Bacteria
Norhopanes	C_{27}–C_{28}	Anoxic marine
2- and 3- methylhopanes	C_{28}–C_{36}	Carbonate rocks
Benzohopanoids	C_{32}–C_{35}	Carbonate environments
Hexahydrobenzohopenoids	C_{32}–C_{35}	Anoxic, carbonate-anhydrite
Gammacerane	C_{30}	Hypersaline environments
Oleananes, lupanes	C_{30}	Late Cretaceous and Tertiary flowering plants
Bicadinane	C_{30}	Gymnosperm tree resins
β-carotane	C_{40}	Arid, hypersaline
Steranes	C_{19}–C_{23} C_{26}–C_{30}	Eukaryote organisms, plants, and animals
24-*n*-propylsterane	C_{30}	Restricted to marine sediments
4-methylsteranes	C_{28}–C_{30}	Marine and lacustrine dinoflagellates
Dinosteranes	C_{30}	Marine, Triassic or younger

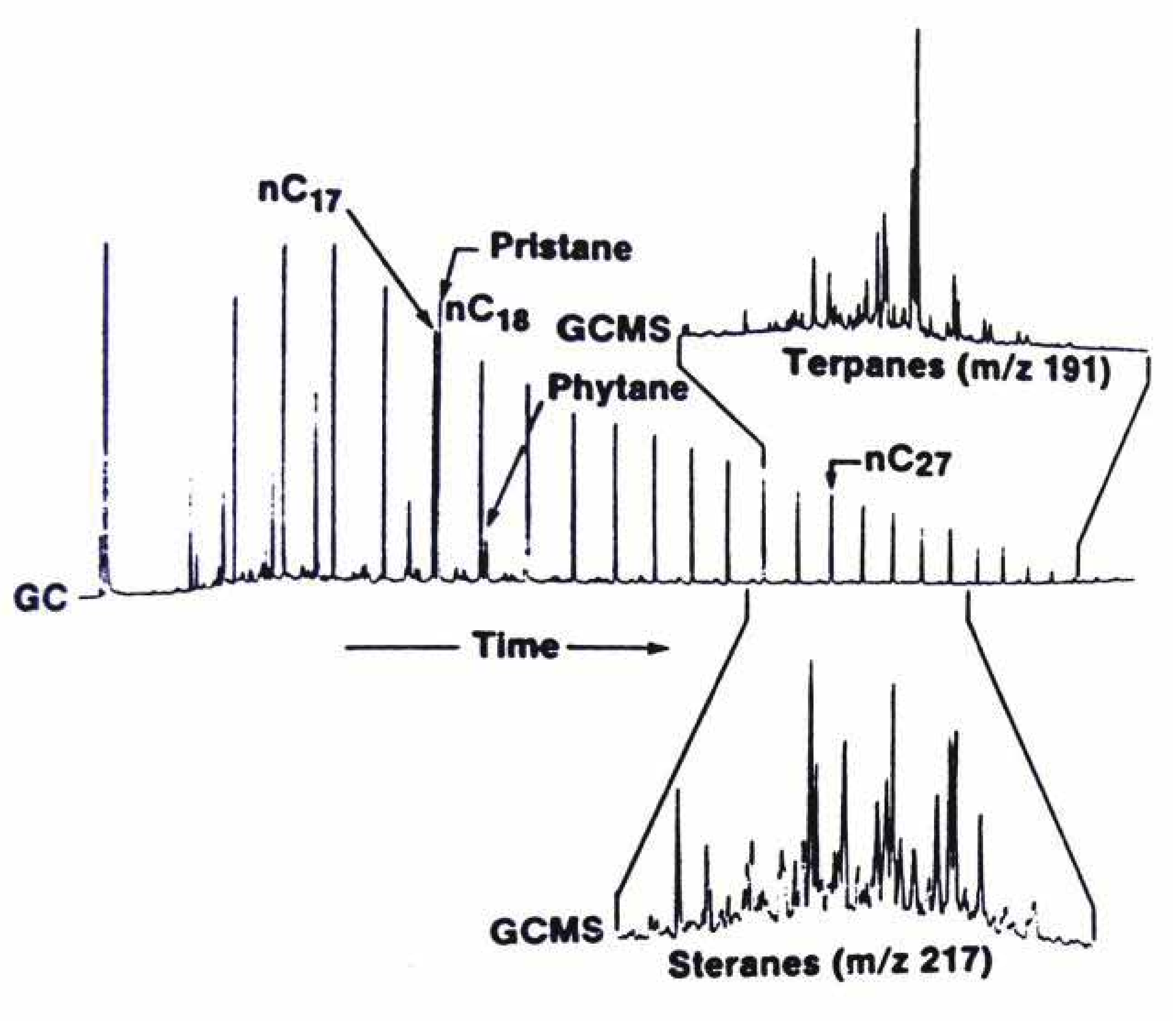

Figure 1 - Biomarkers are shown as distribution of molecular concentration as time proceeds measured by gas chromatography (GC) like alkanes (such as nC_{17}-nC_{27}) and isoprenoids (including pristane and phytane), or gas chromatography-mass spectrometry (GC-MS) like terpanes and steranes. Each pattern of molecular concentration versus time has specific meaning (Peters and Moldowan, 1993).

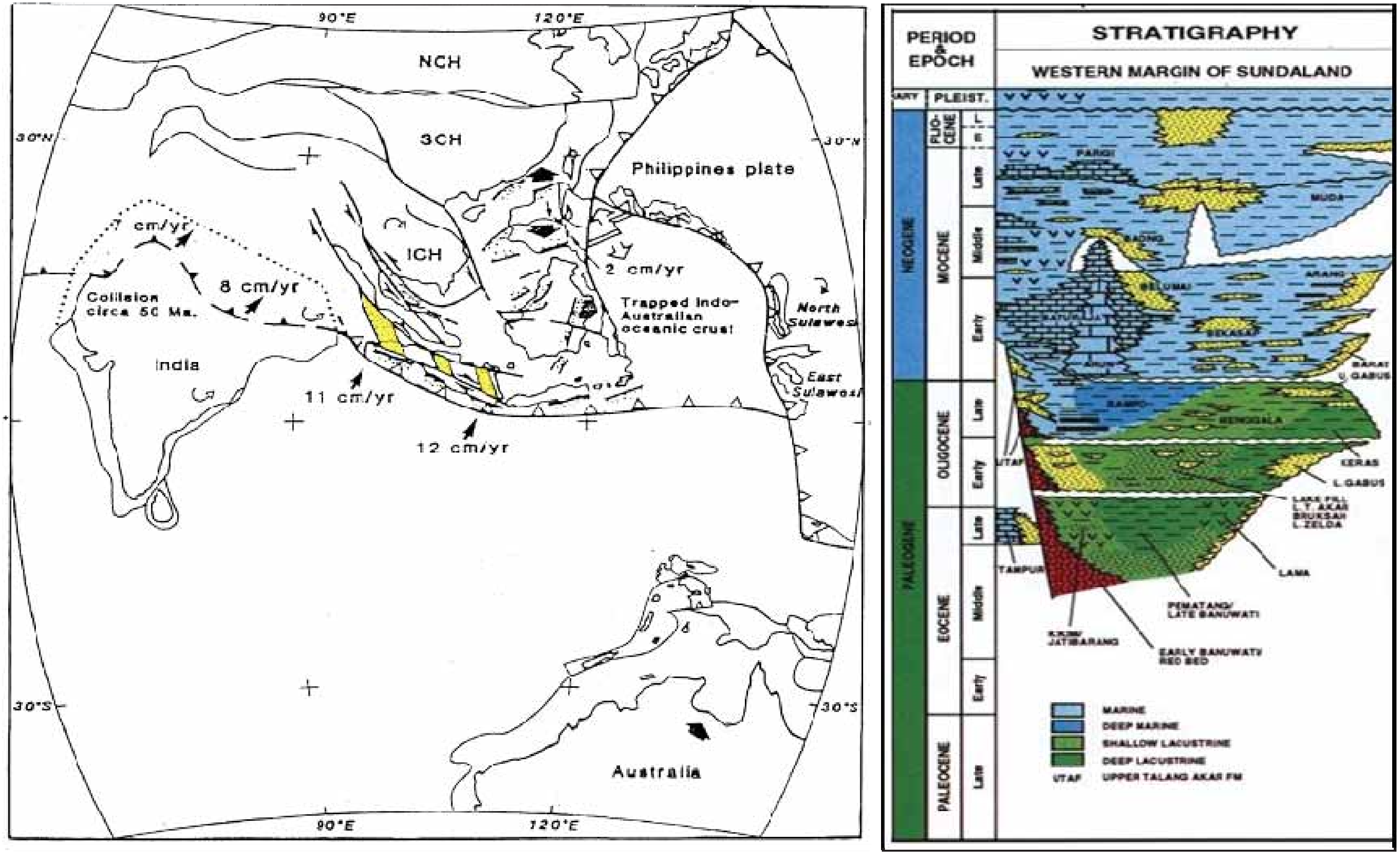

Figure 2 - Map showing Late Eocene reconstruction, 40 Ma. Collision of India has already begun, and SE Asia is deforming internally in response, with creation of numerous sedimentary basins, forming rifted basins of North Sumatra, Central Sumatra, South Sumatra (highlighted in yellow) (Daly et al., 1987). Stratigraphic column showing typical basin stratigraphy of Western Sundaland margin, including Sumatra. Note the development of various depositional environments in rifted basin from Eocene to Oligocene (lake, fluvio-deltaic, marginal marine, open marine) (Sudarmono et al., 1997).

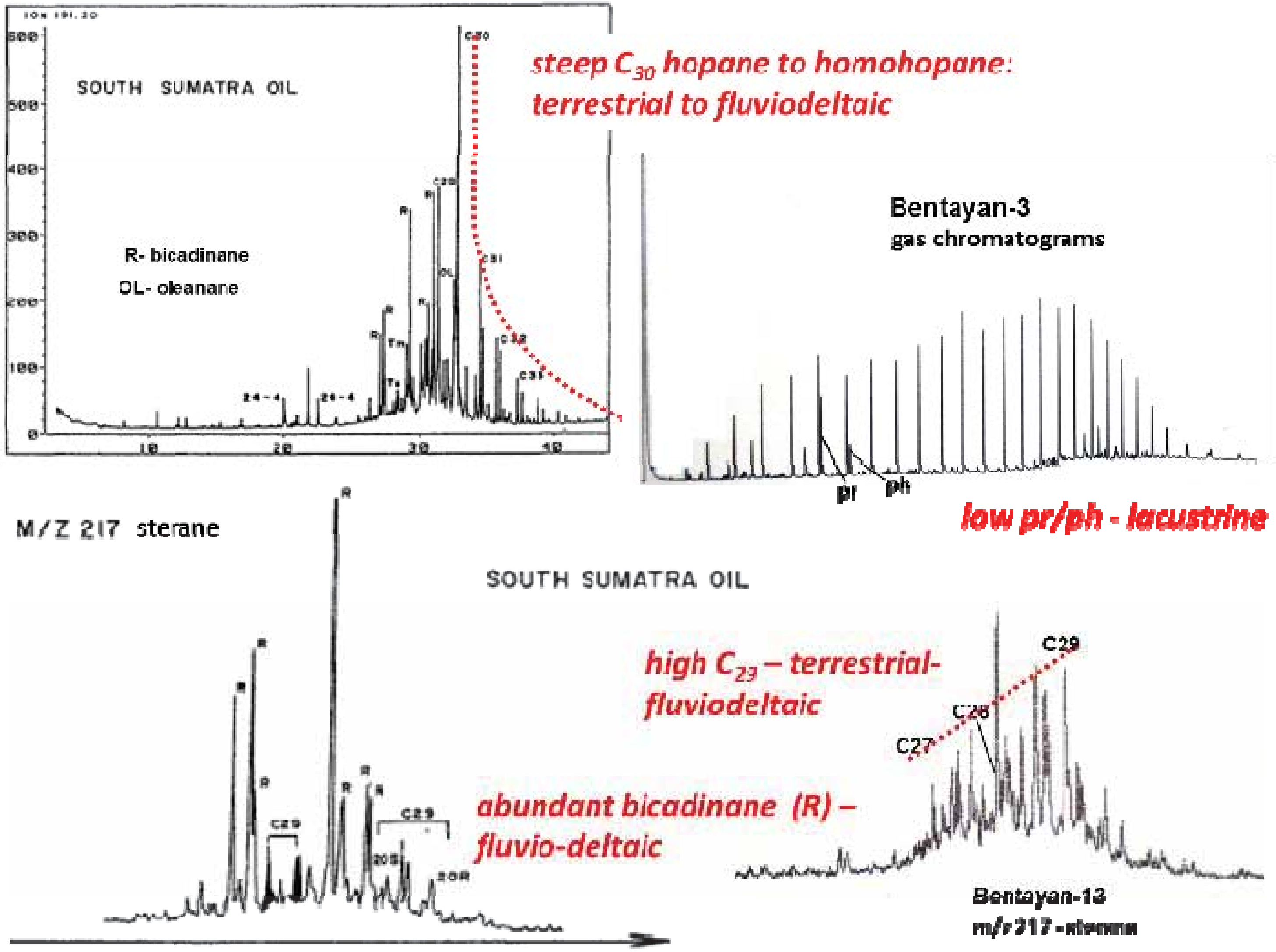

Figure 3 - Biomarker characteristics of South Sumatra oils, showing fluvio-deltaic and shallow lacustrine source facies (Satyana and Purwaningsih, 2013).

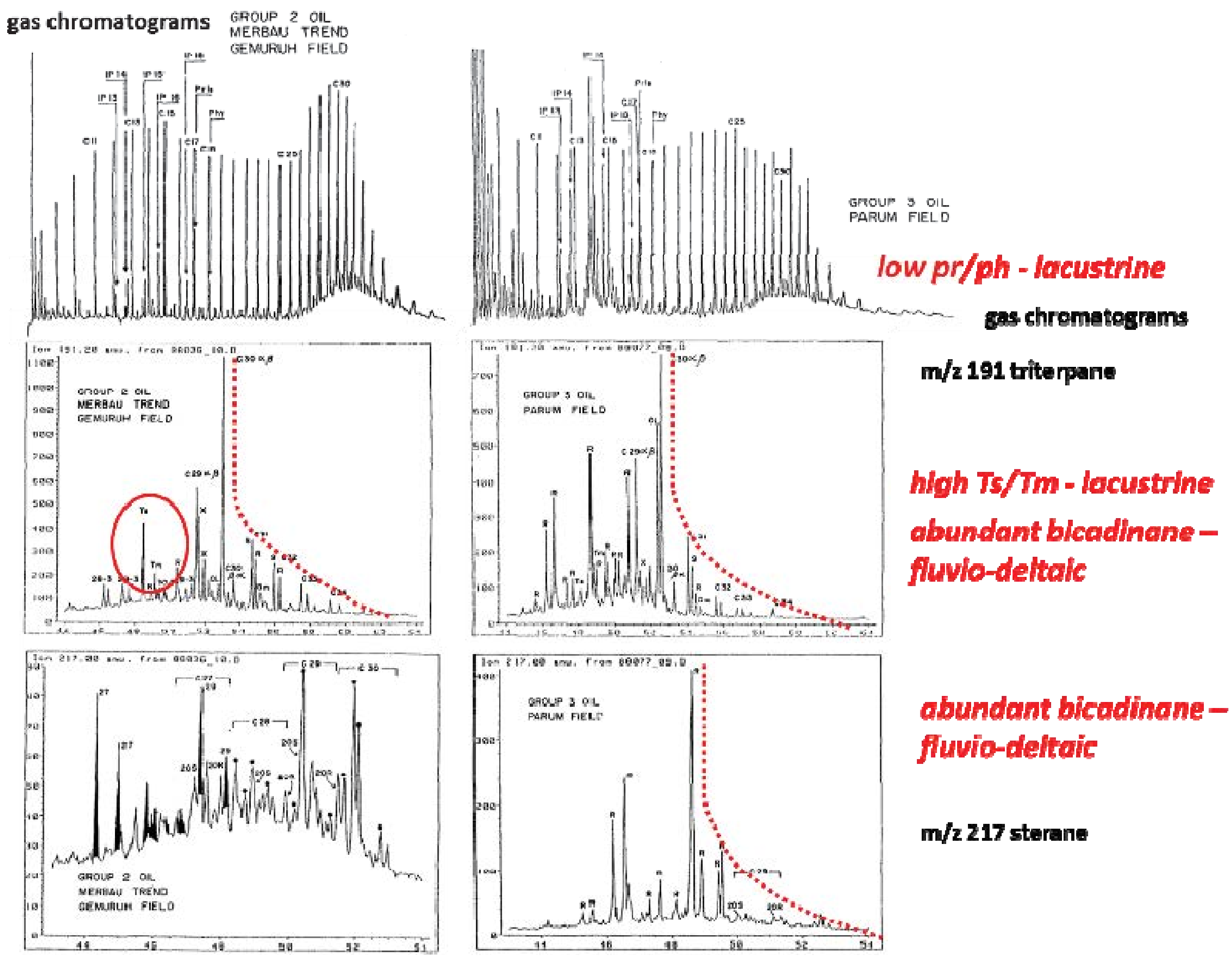

Figure 4 - Biomarker characteristics of Central Sumatra oils, showing lacustrine and fluvio-deltaic source facies (Satyana and Purwaningsih, 2013).

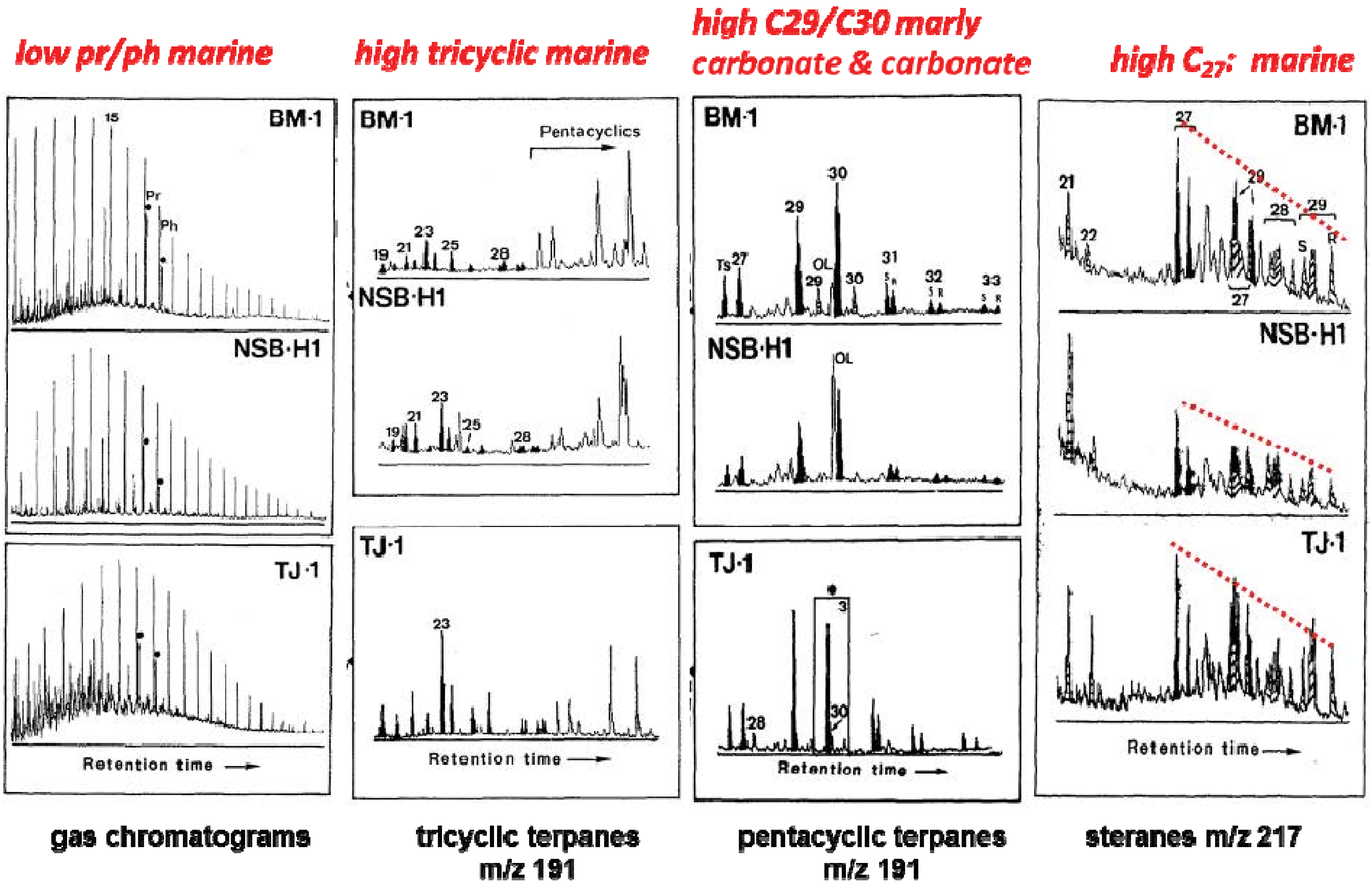

Figure 5 - Biomarker characteristics of North Sumatra oils, showing marine source facies (Satyana and Purwaningsih, 2013).

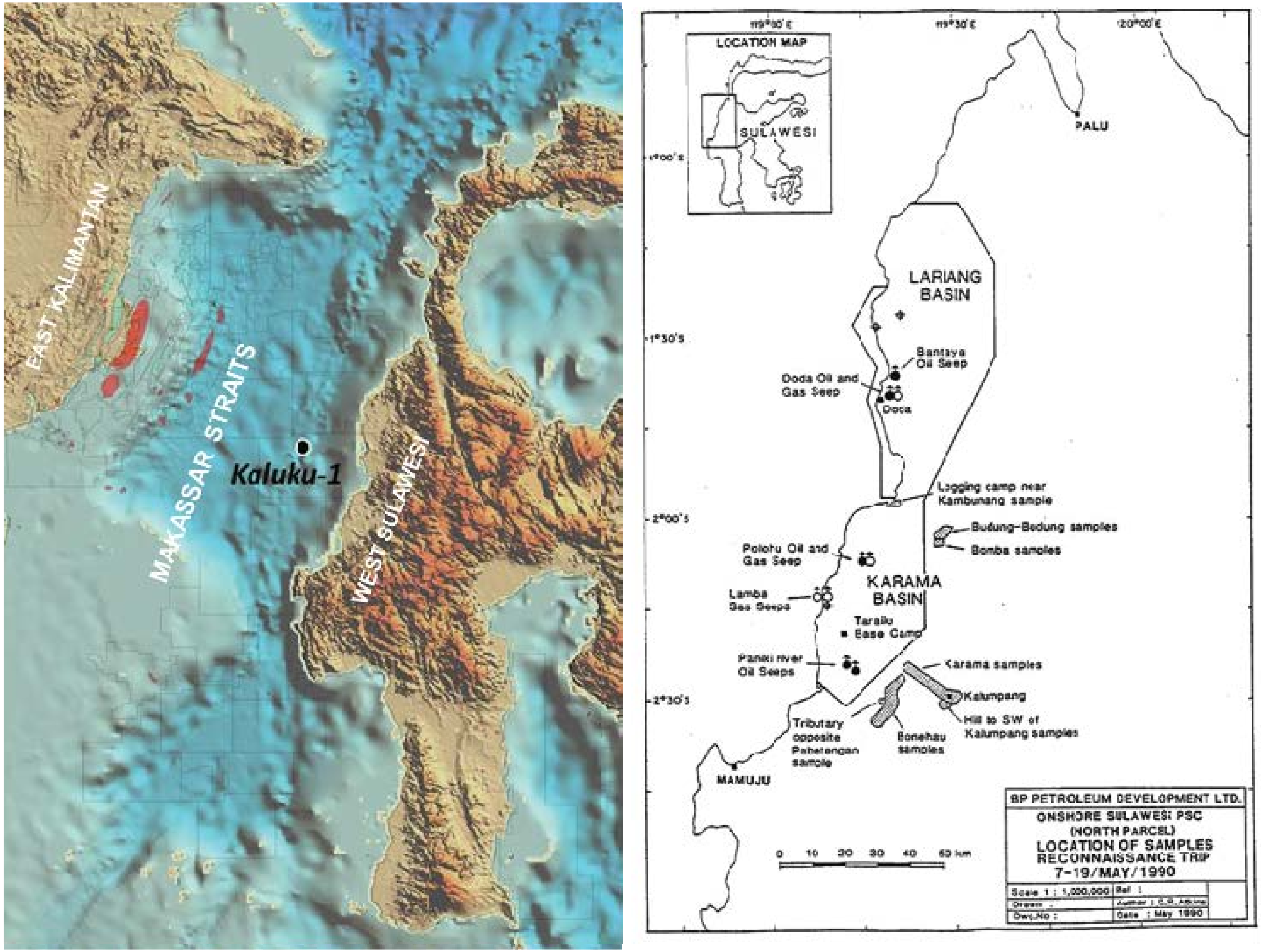

Figure 6 - The Makassar Straits and West Sulawesi onshore area. The location of oil discovery Kaluku-1 well and numerous oil and gas seeps on West Sulawesi onshore are shown. These hydrocarbons have been geochemically analyzed and provide data to derive the evolution of the Makassar Straits.

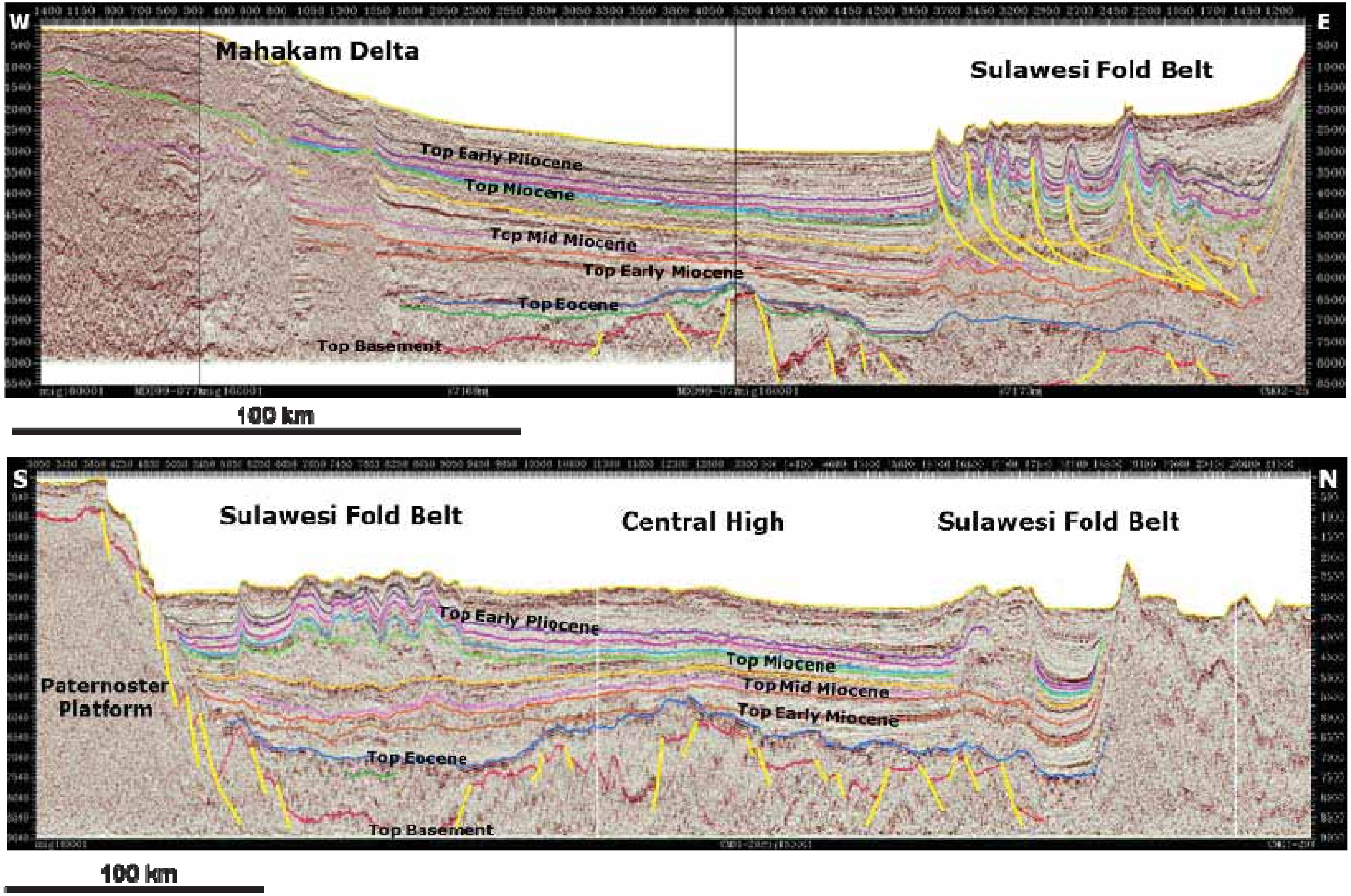

Figure 7 - Regional seismic section across (above: east-west; below: north-south) the Makassar Straits. The section shows rifted basement resulting in horsts and grabens in the Paleogene, and sagging since the Early Miocene onward (Satyana, 2015).

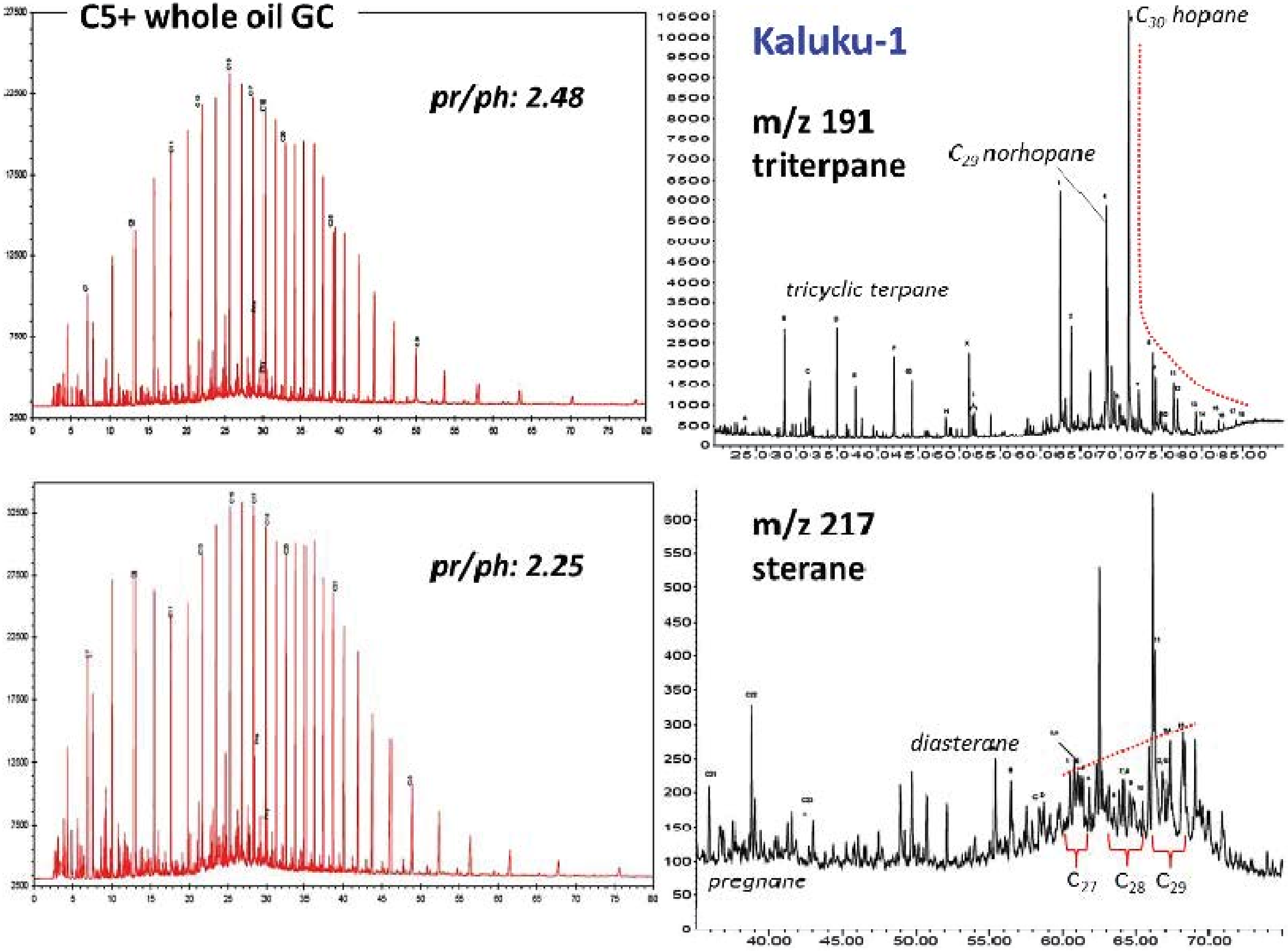

Figure 8 - Biomarker characteristics of Kaluku-1 oils from Eocene horst of the rifted Makassar Straits, showing shallow lacustrine source facies (Satyana, 2015).

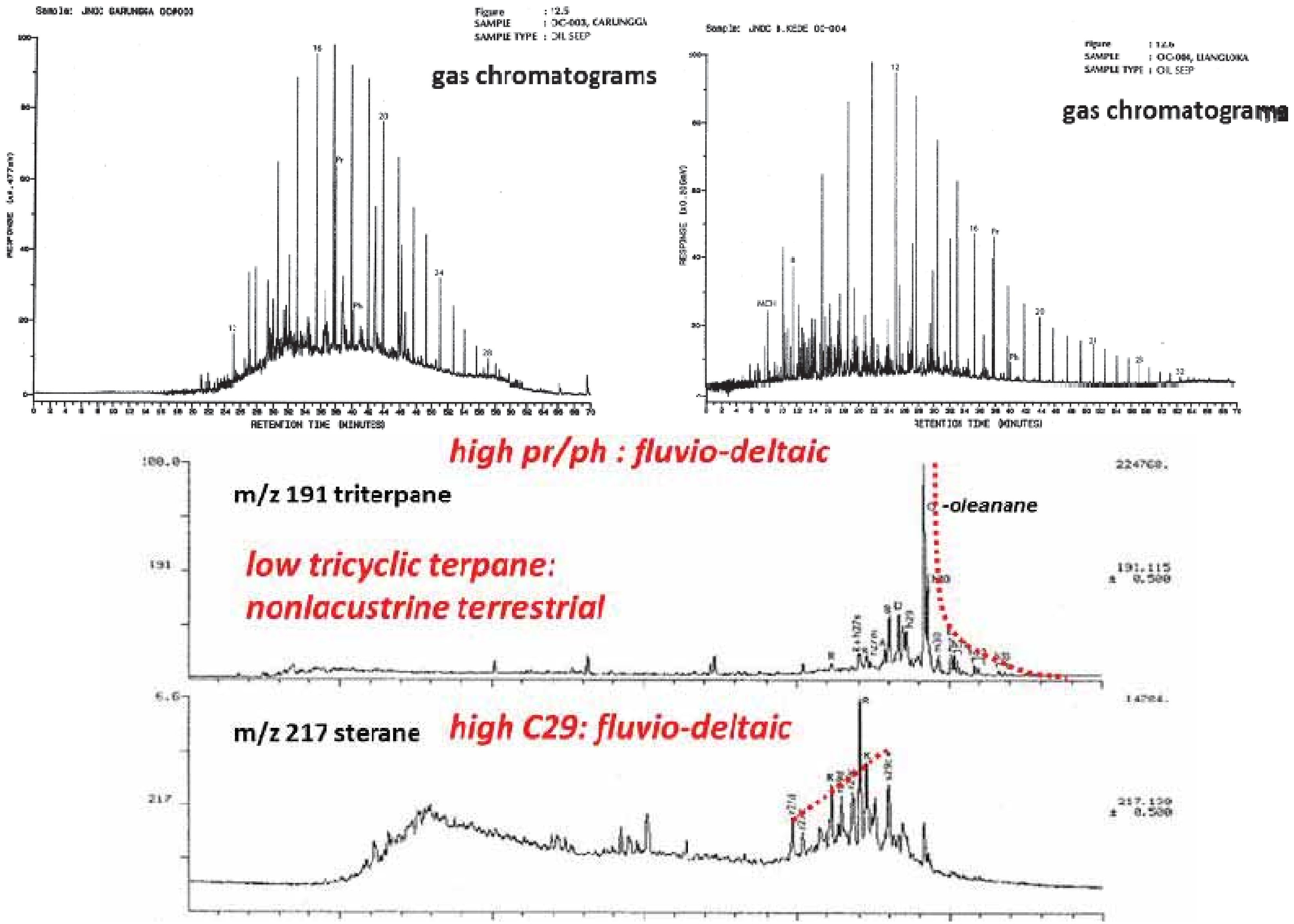

Figure 9 - Biomarker characteristics of West Sulawesi oils seeps, showing fluvio-deltaic source facies, sourced by Eocene coals and deltaic shales.

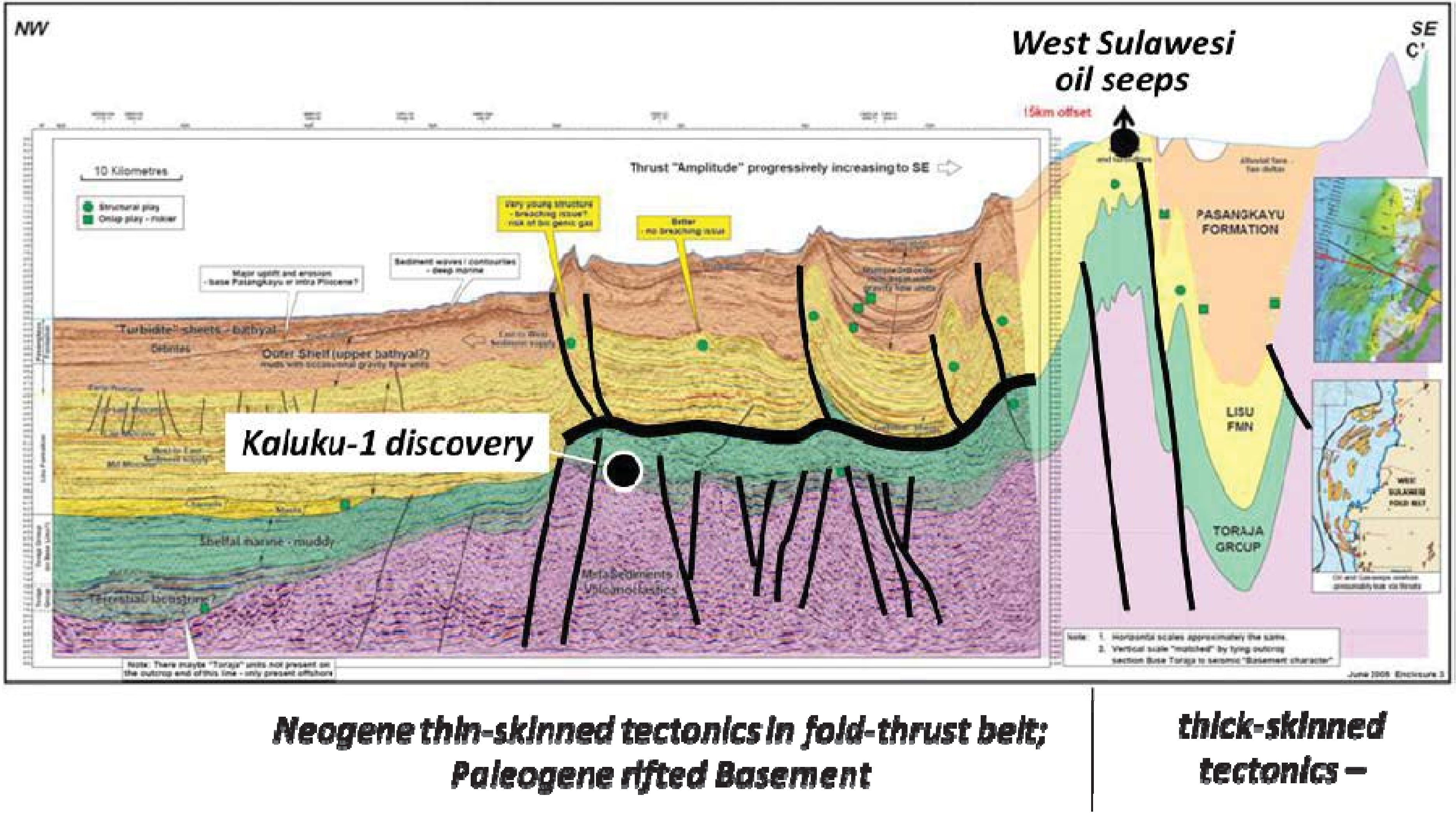

Figure 10 - Implications on the presences of thin-skinned and thick-skinned tectonics in West Sulawesi offshore (eastern Makassar Straits) and onshore areas. Decollement/detachment surface underlying thin-skinned structures will block upward migration from Paleogene sources to enter Neogene reservoirs, hence Neogene plays should have their own source. Whereas, in thick-skinned structures, deep-seated faults can bring generated petroleum from Paleogene sources to Neogene reservoirs (inverted structures).

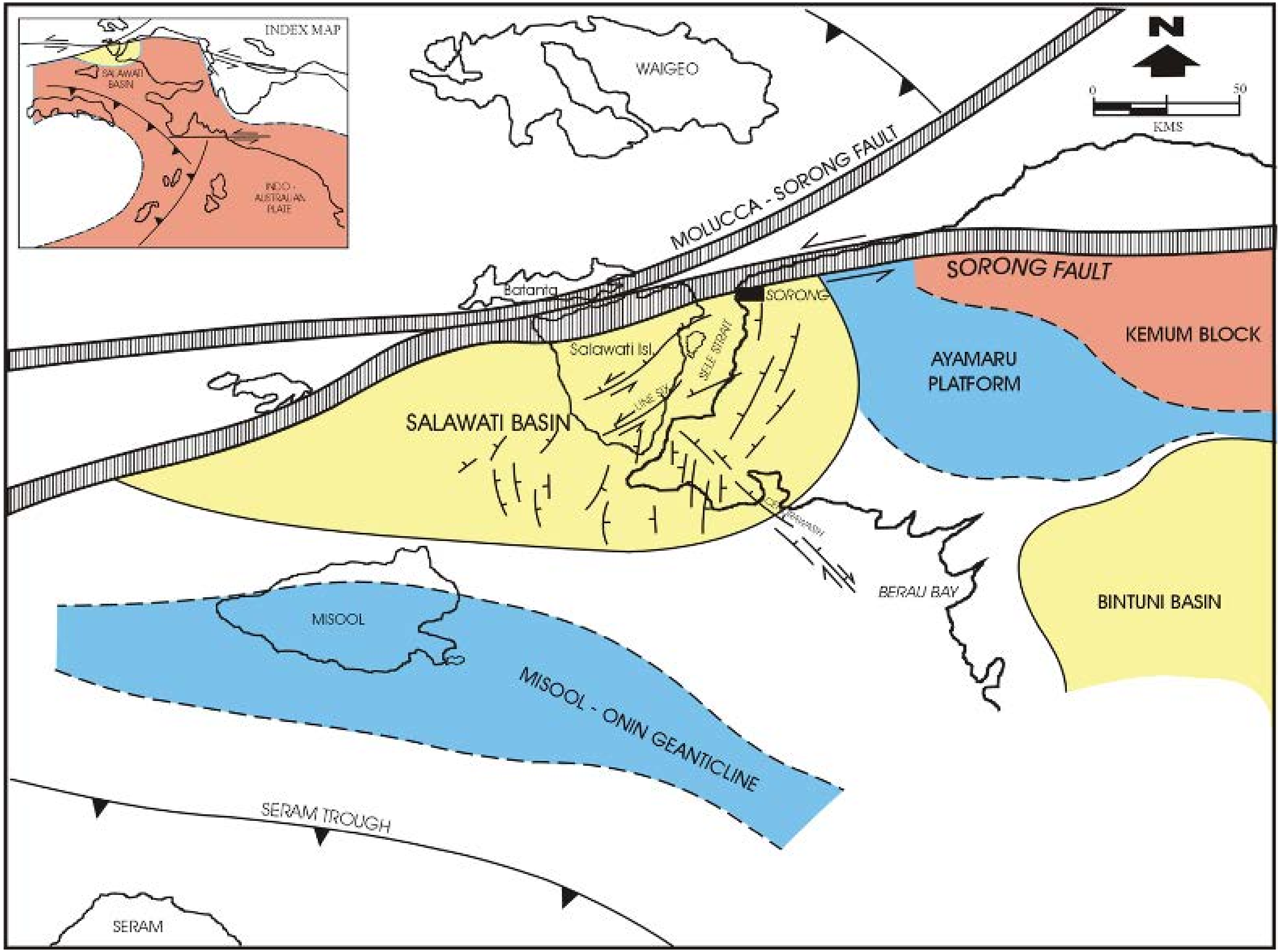

Figure 11 - Tectonic setting of the Salawati Basin showing main geological elements bordering the basin. Note the presence of the major Sorong Fault to the north of the basin - the fault controlled the history of the basin in the Neogene up to the present time (Satyana et al., 2000).

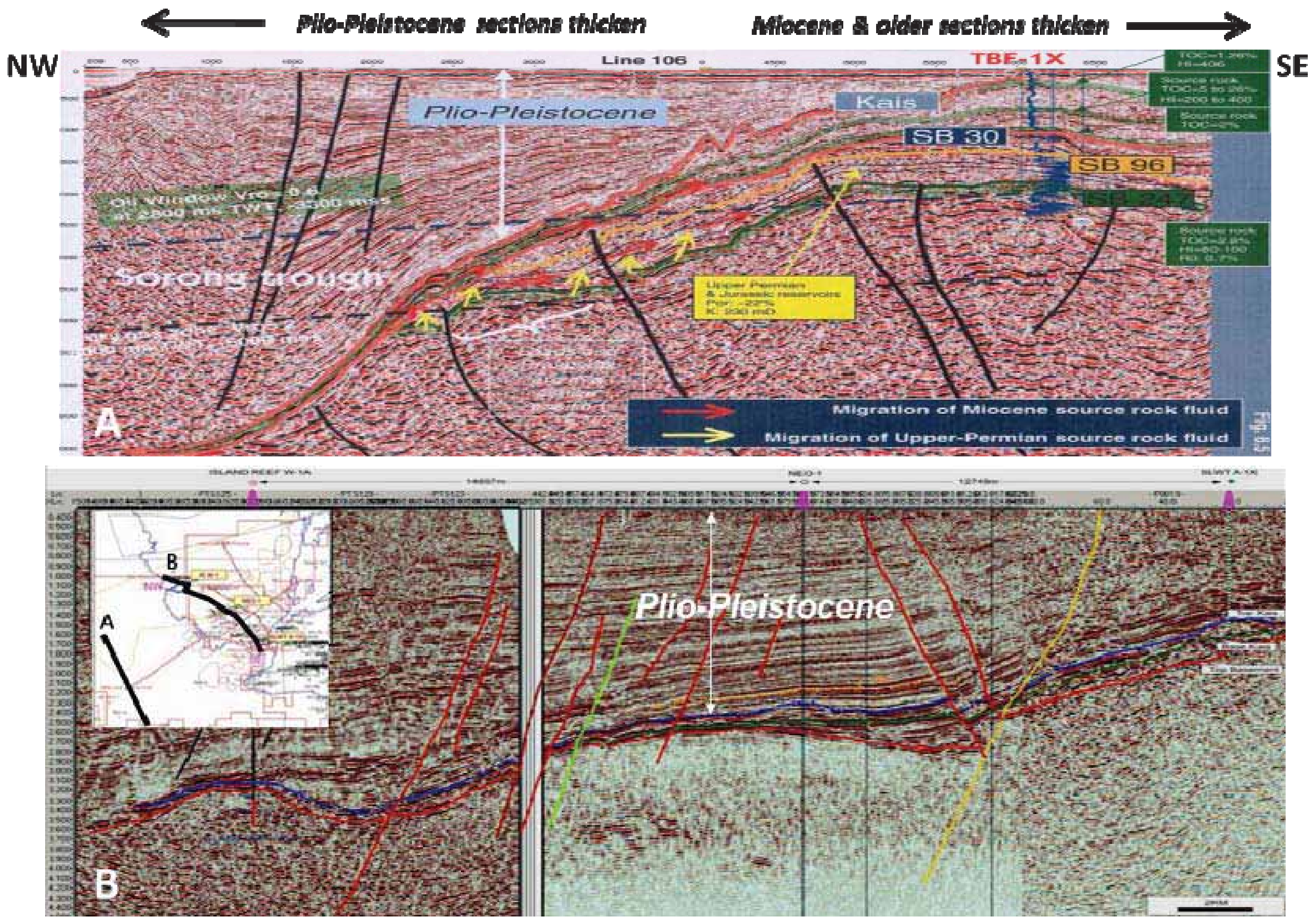

Figure 12 - Seismic sections across the Salawati Basin recording the basin's depocenter reversal. Before the Pliocene, the basin had southern depocenter as proved by southward thickening of pre-Pliocene sections and onlaps of the sections northward-northwestward. Since the Pliocene, the Pliocene-Recents sediments thicken northwestward to the present Salawati Basin depocenter.

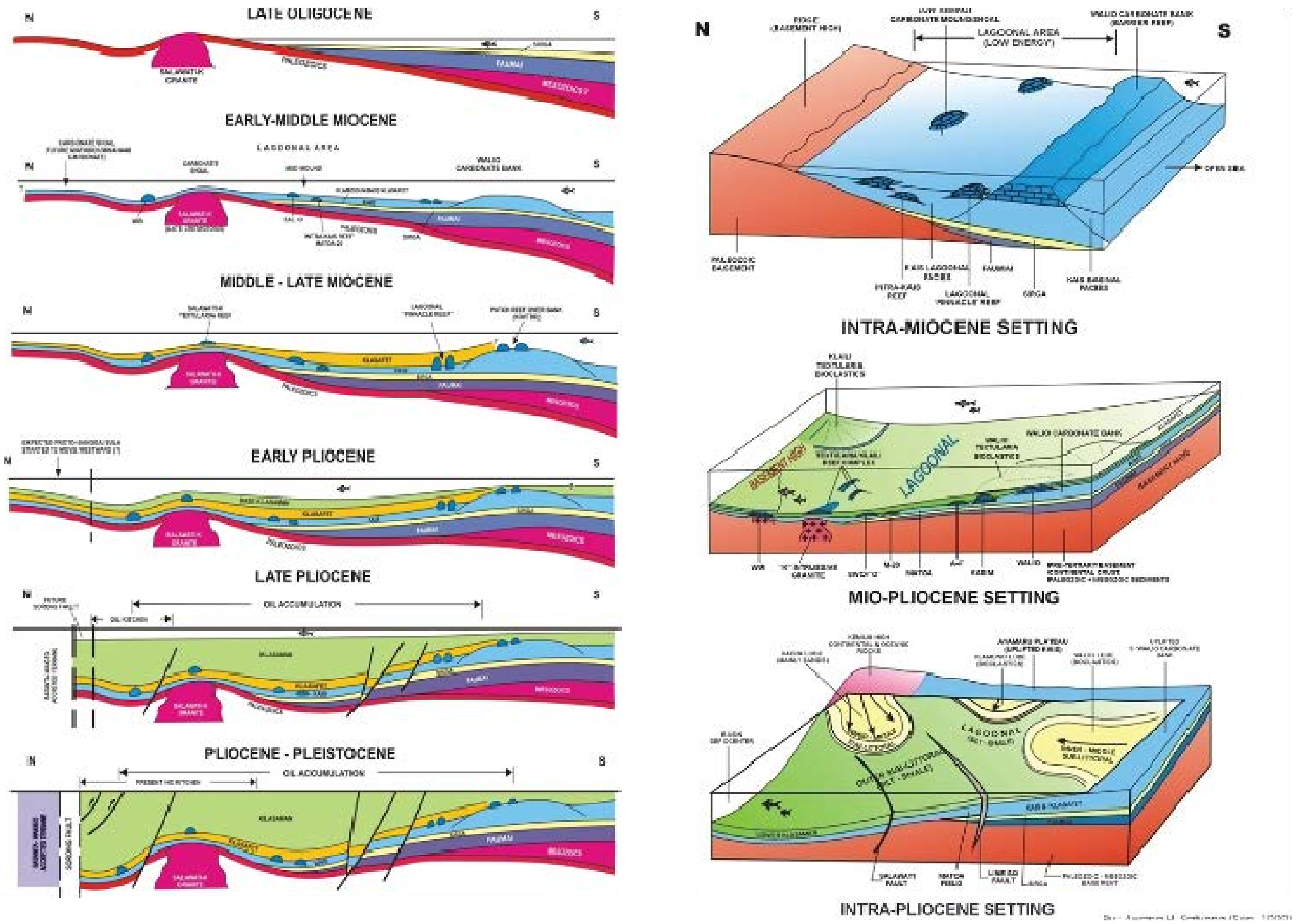

Figure 13 - Schematic section showing the evolution of the Salawati Basin. Note that the basin had southern depocenter from Paleozoic to Late Miocene, as shown by thickening of all sections of Late Miocene and older to the south. In the early Pliocene, as the Sorong Fault initiated its control to the basin, the depocenter started to reverse to the north. In Plio-Pleistocene times the basin has its present configuration with a northern depocenter and it is a site of active kitchen since then. Petroleum has been generated from the kitchen since the mid-Pliocene and migrated updip southward, charging many reefs and faulted carbonates of Kais reservoirs. The proven source rocks are Kais carbonates and Klasafet shales deposited in lagoonal setting during the Miocene before the basin reversal (Satyana, 2001, 2003).

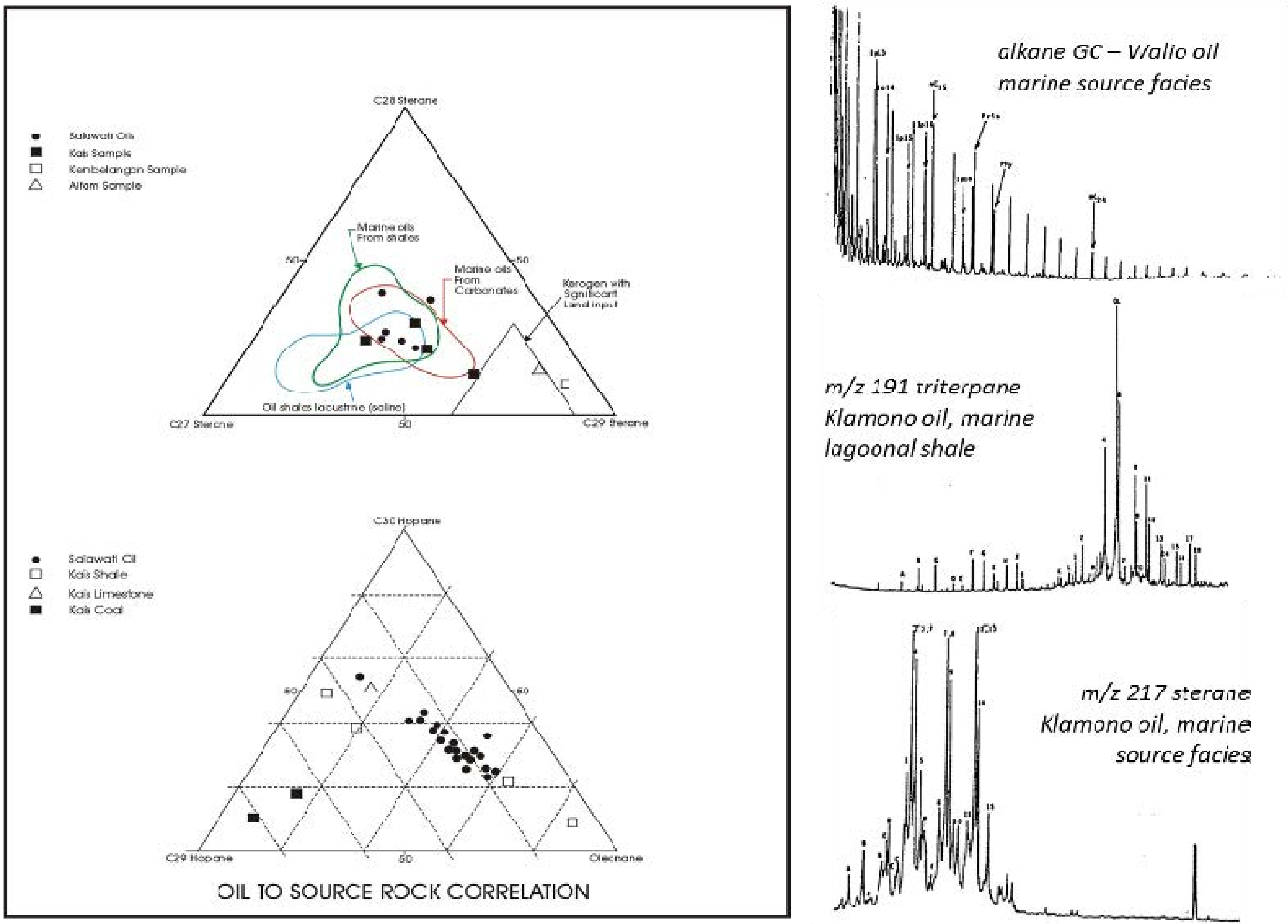

Figure 14 - Biomarker characteristics of Salawati oils, showing marine lagoonal source facies, sourced by Miocene Kais carbonates and Klasafet shales.

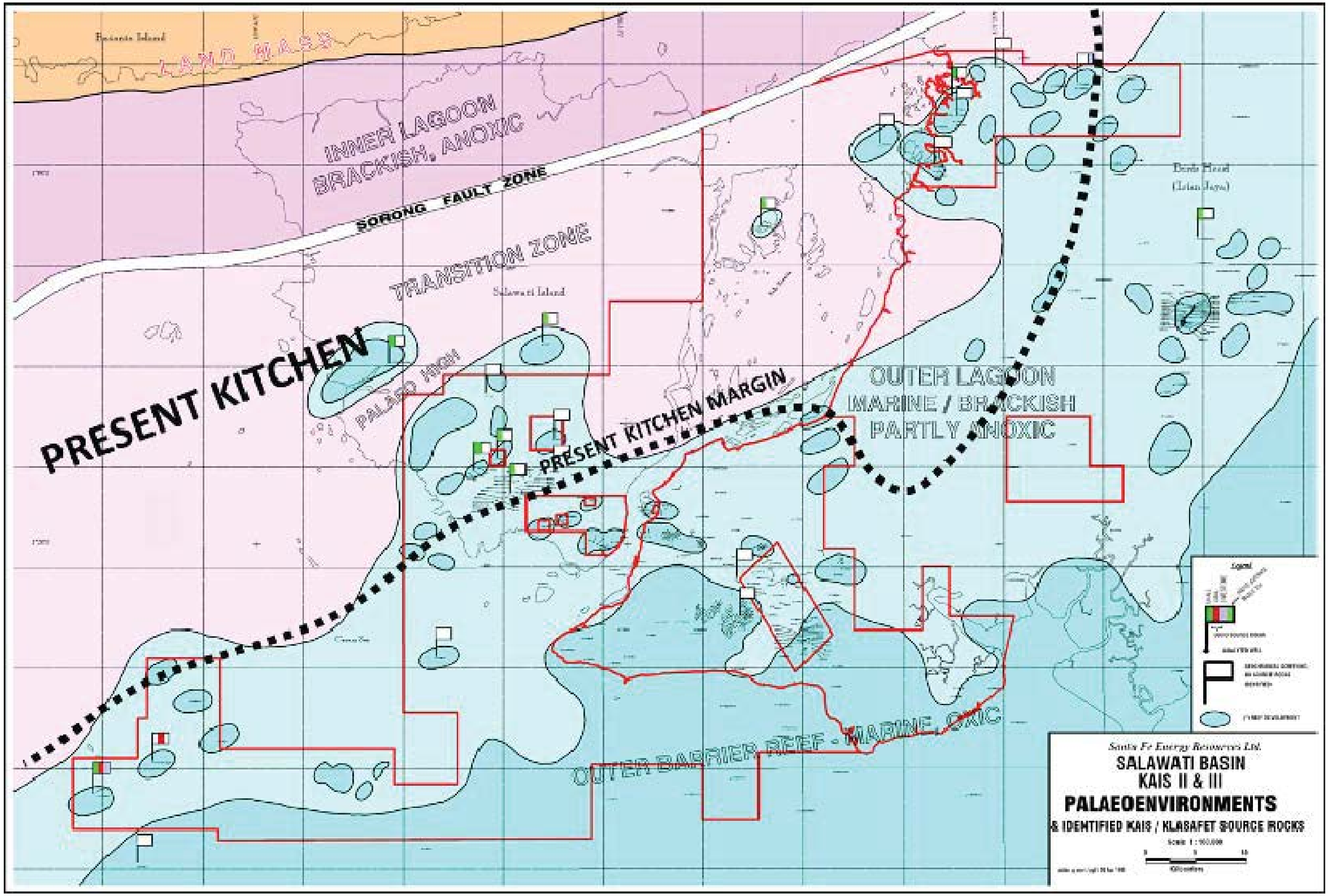

Figure 15 - Paleoenvironment of Kais-Klasafet carbonates and shales. Based on biomarkers, source rocks for Salawati oils were Kais and Klasafet carbonates and shales deposited in transition zone, marginal marine and lagoonal facies. The source facies in the Early Pliocene subsided due to Salawati Basin's depocenter reversal and generated hydrocarbons since mid-Pliocene, migrating to uplifted areas at the south, southwest, east and northeast areas.