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BASIN EVOLUTION AND HYDROCARBON GEOCHEMISTRY OF THE LARIANG-KARAMA BASIN : IMPLICATIONS FOR PETROLEUM SYSTEM IN ONSHORE WEST SULAWESI

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ABSTRACT

This paper presents the results of a number of new studies in the Karama and Lariang onshore basins of western Sulawesi. The basins form part of an original west-facing, extensional half-graben system related to Eocene rifting centered on the Makassar Straits. Extension continued until the basins were inverted in the Plio-Pleistocene, during a contractional event. The majority of shortening was taken up by a suite of NW-SE oriented strike-slip faults which dissect the original extensional basin architecture. These strike-slip faults compartmentalize a series of contractional structures (folds and thrusts) that are related to a localized fold-thrust belt. Where the fold-thrust belt continues into the offshore, it is restricted in aerial extent by the Paternoster Platform in the south and the Palu Fault in the north.

Palaeogene extension started in the Middle Eocene, resulting in deposition of a syn-rift sequence consisting of fluvio-deltaic sands, coals, lacustrine shales and limestones and laterally equivalent basinal marine facies. This sequence is overlain by a marine sequence of shales of Late Eocene to Early/Mid-Miocene age. Extension and contemporaneous intrusion and extrusion of igneous material continued through the Middle to Late Miocene and into the Early Pliocene during post-rift thermal subsidence related to subduction roll-back. Marine conditions persisted into Plio-Pleistocene times and sedimentation patterns became more complex with deposition of shelf muds, gravity flows and volcaniclastics being locally sourced from structural highs which form as contractional folds grow in the inverting basins. Rapid uplift across strike slip faults during this time also led to deposition of debris flows in what has previously been referred to as a foreland basin setting.

The presence of an active petroleum system is demonstrated by the occurrence of oil and gas seeps over major fold structures (Karama and Lariang), and along the faulted, eastern margin of the coastal basin (Karama). These hydrocarbon seeps were generated from source rocks containing terrestrially-derived organic matter such as the Middle to Late Eocene, fluvio-deltaic coals and carbonaceous shale. Geochemical analyses of the oil seep samples indicate they are paraffinic, low sulfur, moderately low wax to waxy oils. The GC-MS biomarker data of two oil seeps from the Lariang Basin were generated from an organic assemblage dominated by terrestrial higher plant material with some minor algal input. The oil seeps from the Karama Basin indicate derivation from a source rock facies containing algal debris mixed with some terrestrial higher plant material and are assigned to oil of an open marine/deep lacustrine source.

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INTRODUCTION

Study Area

The study area is centered on the Lariang and Karama Basins, which are oriented north-south and occupy a narrow coastal plain on the west side of the island of Sulawesi. They lie between the deep-water Makassar Straits in the west and the mountainous interior region of Central Sulawesi in the east (Figure 1). This area has had a long history of investigative studies and the current work integrates these studies with previously unpublished field and technical reports, the interpretation of an onshore seismic survey and unpublished offshore seismic data from the Makassar Straits.

Oil Exploration History

The Lariang and Karama Basins have been explored by a number of companies over the past 115 years. Pre-second world war studies took place in the Lariang-Karama Basin between 1898 and 1900 when the Doda Oil Company drilled a number of shallow wells in the Lariang region. Post-war exploration, including the start of modern exploration techniques, was initiated by Indonesia Gulf Oil in 1970 and taken up by BP in 1974 and Amoseas/Chevron in 1995. The area is currently operated by Tately Budong-Budong N.V. Exploration programes carried out since 1970 have included field work, seismic acquisition and the drilling of five exploration wells. Numerous oil seeps within the Lariang-Karama area (notably in the Doda and Paniki Rivers) were sampled and analysed as part of this study.

The main oil exploration-related field work campaigns were carried out by Gulf (1970); BP (Norvick & Pile, 1976); Amoseas (Chamberlain & Seago, 1995); and Tately Budong-Budong N.V. (Pieters, 2010). In terms of subsurface work, two exploration wells were drilled by Gulf in 1973 (Karama-1 and Lariang-1); one by BP in 1979 (Tike-1) and two by Tately Budong-Budong N.V in 2011(LG-1 and KD-1). Following acquisition of onshore seismic in 2008 by Tately Budong-Budong N.V., the structural model for the region was updated (Seago, 2009) and further field work (Pieters, 2011) has led to an updated palaeogeographic study, which has improved the understanding of lateral facies relationships within the coastal region.

There are numerous published papers which address both regional tectonic processes and stratigraphic schemes forWest Sulawesi and the adjoining areas. The aim of this paper is to present the findings from the recent stratigraphic (well data), structural (onshore and offshore seismic data) and geochemical (sampling and analyses) work and integrate these findings into the established geological history of the region and to formulate a tectono-stratigraphic model and it impacts on the petroleum system in the area.

REGIONAL SETTING

The plate tectonic setting of the region is well described by a number of authors (Luyendyk, 1974; Sukamto, 1975; Hamilton, 1979; van Leuwen, 1981; Piagram & Pangabean, 1984; Powel et al., 1988; Fullerton et al., 1989; Hasan, 1990; Parkinson et. al., 1998; Abdullah et. al., 2000; Elburg et. al., 2002; Robb et. al., 2005; Calvert & Hall, 2007; Hall, 2009; Metcalfe, 2011) and the reader is referred to these published works for background information. A comprehensive explanation of the research history and regional setting can also be found in Hall (2011). At a regional scale, SW Sulawesi was spatially related to Kalimantan and Sundaland (Eurasian Plate) throughout the Tertiary, and eastern Sulawesi formed part of the Indian-Australian Plate, which drifted north eastwards before being accreted to western Sulawesi and the Eurasian Plate in the Early Miocene (Hall 1996) (Figure 2). Deformation of the area was then influenced by uplift and rotation in Kalimantan and uplift in SE Sulawesi before subduction roll-back began in the Mid-Late Miocene (Hall, 2011) and, later, by the developing leading-edge and fault splays of the Sorong strike-slip fault zone. These events play an important role in the structural development of SW Sulawesi during the Tertiary.

In terms of the study area, the initial development of the Lariang-Karama Basin commenced in the Middle Eocene, during a regional phase of rifting centered on the Makassar Straits and at the SE margin of the Eurasian Plate. This rifting event gave rise to the deposition of a syn-rift, Mid-Late Eocene fluvio-deltaic system consisting of sands, coals, lacustrine shales and limestones overlain by a post-rift, Late Eocene-Early Miocene marine shale sequence. Marine conditions persisted throughout the Late Miocene/Early Pliocene and the area was subjected to continued extension and volcanic activity during the post-rift, thermal subsidence stage. Mild basin inversion in the Makassar Straits in the Middle Miocene coincides with an unconformity onshore, but the timing is too late to be attributed to collision events in SE Sulawesi (e.g., accretion of the Tukang Besi Plate), which was already engaged by the Early Miocene. Similarly, regional uplift in Kalimantan also predates the formation of the unconformity. This Middle Miocene unconformity is temporally related to the early stages of roll-back of the subduction zone in SE Sulawesi (Spackman & Hall, 2010; Hall, 2011), which commenced at ~15 Ma and coincides with thermal subsidence, extension and volcanic activity in SW Sulawesi during the post-rift Late Miocene - Early Pliocene. A change from extensional to contractional deformation occurred at ~2 Ma and continued through the Plio-Pleistocene. During this time, the NW-verging West Sulawesi fold and thrust belt formed, and was further compartmentalized by associated large-scale movement on transfer faults that link with the westward termination of the regional scale Sorong Fault Zone. Further to the north, the Sula Platform was being subducted (Figure 2).

STRATIGRAPHY

The stratigraphic nomenclature in this paper (Figure 3) follows that of Calvert (2000). Lithological descriptions are based on Pieters (2010). The distribution of the stratigraphic units in and around the study area is shown on a regional geological map (Figure 4). This map is an amalgamation of various new data sets, using the geological map of Calvert (2000) as a base.

Mesozoic and Cretaceous Basement

The Mesozoic basement in the Lariang and Karama region consists of gneiss, schist, quartzite, phyllite, marble and slate. It is unconformably overlain by Upper Cretaceous shales and pyroclastic and volcaniclastic rock with fragments of aphanitic, amygdaloidal and phyric lava with fine phenocrysts of plagioclase and pyroxene. The volcanics are considered to be laterally equivalent to meta-sedimentary basement in other parts of western Sulawesi.

Tertiary Toraja Group

The Toraja Group, which rests unconformably on Mesozoic or Cretaceous basement is separated into the Budung-Budung Formation, an extensive marine sedimentary sequence, and the Kalumpang Formation, a terrestrial sedimentary sequence.

a. Budung-Budung Formation

Description

The Middle Eocene to Early Miocene Budung-Budung Formation consists of bathyal mudstones, sandstones, conglomerates and minor bioclastic limestones. The lower part of the formation ranges from clay to silt.The clays are grey to dark grey. Occasionally, the mudstone is associated with muddy coal. The mudstone can be calcareous or non-calcareous; when calcareous, the mudstones contain planktonic foraminifera and nannofossils. Structureless sands also occur, although very infrequently. The sandstone is fine to very coarse-grained and in places gritty to pebbly, particularly at the scoured bases of thick or massive beds. Coarser facies include granule conglomerates, which occur at the base of massive sandstone beds and matrix-supported conglomerates, which are restricted to the base of the unit (Calvert, 2000). Limestones are also present and can be divided into bioclastic packstones and wackestones containing coral alga, pelecypod debris and microfossils. The upper part of the formation is mostly made up of mudstone and minor, thinly bedded, fine-grained sandstone with intercalations of tuff and volcaniclastic sandstone indicating local volcanic activity.

The Budung Budung Formation was penetrated in the KD-1 well, which encountered a thick section of mudstone, carbonaceous mudstone with interbedded sandstone, siltstone and limestone.

Depositional Environment

The Middle to Late Eocene sediments of the Budung-Budung Fm. are interpreted to have been deposited during a phase of extensional faulting (rifting) in an inner to outer neritic (upper bathyal), marine shelf environment Sands were deposited rapidly from turbidity currents or storm-related sediment plumes, whereas mud was deposited by suspension fall-out or by fluctuating current velocities. Carbonaceous material was washed into the basin from nearby land.

b. Kalumpang Formation

Description

The Middle-Upper Eocene Kalumpang Formation is composed of a clastic sequence of shales, coal beds and metre-thick quartzose sandstones.

The thick, massive sandstones are white to light grey and light brown. The base of the beds is commonly abrupt, planar, scoured or undulating with coarse-grained to gritty or conglomeratic sandstone and locally fine conglomerate with rip-up mud chips and coal fragments. The sandstone grains are sub-rounded to sub-angular and fine to coarse-grained. They are generally non-calcareous and mainly composed of variable amounts of feldspar and quartz with minor amounts of sedimentary (argillite, quartzite, chert) and igneous (andesite/basalt, diorite) rock fragments, micas (biotite and white mica), opaques, and heavy minerals. Siderite nodules, mostly oxidized to limonite patches, have been observed locally. The sandstones are commonly structureless (massive) and in places lenticular and channelised with decimeter-scale, low-angle, planar cross-bedding.

The brown-red and grey mudstone/shale is mostly structureless and occasionally calcareous and varies from pure clay to silty/sandy clay, and contains thin interbeds of fine-grained sandstone.

Coal seams are interbedded within the mudstone-sandstone successions, where they can reach thicknesses of up to a few meters. For instance, Calvert (2000) reports a coal seam 6 m thick. The coal seams are generally sandwiched between carbonaceous mudstones that contain plant fragments.

No wells drilled to date penetrate the Middle Eocene of Kalumpang Formation.It is only observed at outcrop in the mountainous SE area around Kalumpang. The Kalumpang Formation passes laterally into, and is conformably overlain by, the Budung-Budung Formation.

Depositional Environment

The Kalumpang Formation was deposited in a swampy marginal marine environment. Pollen in the coal suggests a brackish water environment (Calvert, 2000). The thick sandstone deposits are thought to represent broad fluvial-deltaic channels, with the siderite being formed in reducing conditions associated with a fluvial-dominated, deltaic swamp environment. The interbedded mudstone and sandstone were deposited in overbank/slope areas of the delta within a reducing, littoral environment with periodic inputs of sandstone by sediment gravity flows. The bio-clastic limestone is interpreted to represent biohermal deposits accumulated in near shore shallow marine conditions during periods of low clastic input or on submerged fault block footwall highs that were protected from clastic contamination.

Lisu Formation

Description

This formation has a Middle Miocene to Early Pliocene age. It is composed of mudstone, sandstones (greywackes) with minor granule to pebble conglomerate, limestones and volcanics. Mudstones are commonly calcareous or tuffaceous and contain feldspar, biotite. In places, the mudstones arecarbonaceous. The sandstones are polymictic (typically volcaniclastic), with grains of feldspar, mafic minerals, carbonate, minor quartz and lithics. The pebble conglomerates are mostly sub-rounded to sub-angular and poorly to moderately sorted. The clasts consist mostly of argillites, slates, volcanics, metamorphics and aphanitic, silicified rock thought to be derived from the Late Cretaceous basement. The limestone is bio-calcarenite and generally consists of fossil and carbonate clasts with minor lithic fragments of biotite and feldspar.

The lowest part of the Lisu Formation is lithologically similar to the top of the Budung-Budung Formation and is dominated by mudstone. In contrast to the Budung-Budung Formation, the Lisu Formation is dominated by shelf mudstone.

In the KD-1 well, the lithology of the Lisu Fm is predominantly claystone interbedded with sandstone, siltstone, volcanics and limestone. The volcanics occur within the Upper Miocene section (similar to outcrop) with an interval thickness of 50cm-15m. Volcanics are light grey, light green, medium grey, occasionally colourless, hard and brittle with a cryptocrystalline, felsic groundmass and scattered inclusions of very fine biotite and other mafic minerals. They are locally epidote-rich, and contain zeolites and rare pyrite concretions. Siltstones are light brown to light brownish grey, firm, moderately hard, friable, and sub-blocky with commonly scattered extremely fine pyrite and very fine-fine brown-black biotite.

Depositional Environment

The sediments of the Lisu Formation were deposited in a neritic, submarine, shelf environment in which deposition of sand was primarily from gravity (debris) flows (delta turbidites). Deposition of mud was mainly from suspension fall-out.

Pasangkayu Formation

Description

The latest Early Pliocene/Pleistocene Pasangkayu Formation reflects the overall shallowing and filling of the basin and is dominated by conglomerates, sandstones and mudstones. The conglomerates are both matrix and clast-supported and contain clasts ranging in size from pebbles to cobbles which are commonly sub-rounded to sub-angular and poorly to locally moderately sorted. The polymictic clasts consist mainly of basement rocks including Late Cretaceous argillite, slate, silicified aphanitic rocks, minor metamorphics, volcanics and intrusive rocks of felsic (granitoid) and mafic composition. The mudstone is commonly silty or sandy, carbonaceous and the internal structure varies from massive to thinly bedded or laminated. The different lithologies show a consistent distribution about the basin, with conglomerates mostly exposed along the mountain front in the east and mudstones in the west. It can be concluded that the source area is the topographic basement high in the east and that basinward, the clastics progressively become finer. This westward flow is supported by the orientation of large scale clinoforms in the onshore 2D seismic data.

The formation is unconformable with older rock units and is itself unconformably overlain by Quaternary alluvium. The Pasangkayu Formation was not recorded in the KD-1 well as it was spudded in the Lisu Formation.

Depositional environment

The depositional environment is interpreted to be an inner to outer neritic, high-relief basin with a nearby hilly to mountainous hinterland in which debris (mass) flows carried large amounts of coarse detritus. The presence of a high proportion of sub-rounded clasts in the conglomerates suggests a less proximal source than the immediate basin edge. It is possible that major rivers carrying more mature sediments by-passed the mountain front or there was reworking of a slightly older deposit (fan, talus). The finer sediments (sandstone and mudstone) cap the high-energy deposits and/or were deposited by lower energy debris flows, while generally the mudstone-rich facies sediments were deposited deeper in the basin.

BASIN EVOLUTION AND STRUCTURAL STYLE

Syn-rift Phase (Middle Eocene)

Rifting began in the Middle Eocene in SW Sulawesi (Situmorang, 1982; Hall, 1996; Guntoro, 1999) and led to formation of the Makassar Straits, which separates West Sulawesi from East Kalimantan. During rifting, marginal marine to shelf, clastic sediments were deposited in NE-SW trending half-grabens. Limestones developed on the crests of uplifted footwall fault blocks and fine clastics accumulated in the deeper parts of each sub-basin. Extension occurred along a NW-SE axis and extensional faults trend NE-SW and dip basin ward to the NW.

In the Middle-Late Eocene, the sediments making up the Kalumpang Formation were deposited in a fluvio-deltaic to shelf environment in the SE of the Karama Basin. In other parts of the basin, only deeper basinal facies have been recorded to date. From south to the north, the depositional environment deepened and, in the north of the Karama Basin and the Lariang Basin, the environmental conditions are more marine/shelf (Budung-Budung Formation) with the presence of limestone shoals surrounded by a muddy substrate.

The distribution of the Kalumpang Formation is limited and it only occurs along the Karama River and around Kalumpang in the SE of the area. None of the five wells drilled in this study area penetrated the Kalumpang Formation. However, KD-1 encountered Eocene basinal facies that are time-equivalent to the fluvio-deltaics, illustrating the close proximity of the two facies, probably across a major fault block. It is possible that the fluvio-deltaic Kalumpang Formation is not well developed in the coastal basins, and that the Eocene-Oligocene stratigraphy here is represented only by a marine facies (Figure 5). In this case, the margin of the coastal plain, where it meets the mountain front, would have been the original edge of a sub-basin in Mid-late Eocene times. However, the presence of continental Kalumpang Formation to the west of the mountains (beneath the coastal plain and in the subsurface offshore) cannot be ruled out, as the base of the Eocene has not been penetrated in wells.

Post-rift Phase (Oligocene-Early Pliocene)

Rifting ceased in the Late Eocene-Lower Oligocene. In the south and in the KD-1 well, Oligocene/Middle Miocene clastics of the Budung-Budung Formation were deposited in marine (neritic-bathyal) conditions and the sediments are dominated by mudstone, limestone and sandstone. In the north part of the Karama Basin, the sediments are finer and include mudstone, marlstone and very fine sandstone indicating overall deepening paleobathymetric conditions from south to north.

The KD-1 well shows a break in the stratigraphy at the top of the Budung-Budung Formation and the presence of a Mid-Miocene unconformity at around 12 Ma. In terms of timing, this unconformity is later than the initiation of rotation in Borneo, but occurs at approximately the same time as the initiation of subduction roll-back.

Continued extension along with a period of thermal subsidence and extension-related volcanism occurred during the Late Middle Miocene/Early Pliocene. During this time, the half-grabens were draped by a clastic sequence in an outer neritic shelf to slope environment (Lisu Fm.) (Figure 6).

Uplift in Kalimantan during the Early Miocene caused sediments to prograde eastward from Kalimantan towards the North Makassar Basin and West Sulawesi. Fine siliciclastic turbidites are encountered in Middle Miocene section in the Tike-1 well. These sediments are thought to be distal equivalents to the sediments of the Kutei Delta in Kalimantan. The significant change in depositional environment from neritic-bathyal in the Oligocene/Mid Miocene to inner-middle neritic in the Late Miocene/Early Pliocene is believed to be caused by uplift in Kalimantan. At the same time, minor tectonism and the onset of high-potassium volcanism in West Sulawesi related to Late Miocene extension (Bergman et. al. 1996; Bellier et. al. 2006; Polve et. al. 1997) resulted in deposition of reef complexes around emergent volcanic centres.

Basin Inversion and Contraction (Late Pliocene-Pleistocene)

During the Late Pliocene, a major deformation event with related uplift affected SW Sulawesi. Contractional structures occur throughout the offshore area, in the coastal basins, and further inland. These structures occur within a NW-transported imbricate thrust stack that is related to a shallow decollement in the offshore region, SE facing and verging asymmetric folds and related thrusts in the Miocene to recent units in the coastal region, and repeated stratigraphic sections separated by thrusts in the hinterland (Figure 7). The pre-existing architecture of a west-dipping zone of extensional half grabens has been 'decapitated' by a series of shallow SE-dipping thrusts. As the deformation frontmigrated through SW Sulawesi, the shallow coastal basins inverted with SE vergence (Figure 8). The thrust zone is not wide, but is segmented by a number of NW-SE oriented transfer faults that compartmentalize the whole area into zones with contrasting deformational styles. Many of these structures can be seen in the onshore seismic data, and folds and thrusts rotate in plan view towards them indicating their late phase of movement (Figure 4). The dominant structures of the area are thought to be the transfer faults.

As they moved, they produced localised highs of significant relief, which created sedimentary source areas for the adjacent deep basins. The NW-SE transfer faults may have been an original fabric in the extensional syn-rift basin, acting as transfers to the main extensional faults. However, during the Plio-Pleistocene, they were re-activated and became sinistral strike slip faults, possibly linked to sinistral movements along the Sorong Fault Zone which enters S Sulawesi at this time.

During this final deformation episode, the sediments have a two-fold source, being locally derived from the SE (rising mountains above the thrust belt) and also from the NE, related to movement and local uplift along transfer zones (Figure 8). This is reflected in the palaeoflow directions (from SE and NE) and the overall fining of the sequence towards the NW.

The uplift event is recorded in the LG-1 well by an unconformity in the Late Pliocene, across which significant changes of the depositional environment occur. The area changes from neritic to upper bathyal in the Pliocene to middle to outer neritic in the Pleistocene. This is not regarded as a regional event, as rapid changes in relief occurred as structures grew in the inverting basins and high relief drop-offs occurred adjacent to transfer faults.

GEOCHEMISTRY

Five coal samples from the Kalumpang Formation were analysed and show very high organic richness (54.88-84.20 wt.% TOC) and excellent hydrocarbon source potential (S_1+S_2 103.56-228.87 mg HC/gm rock). Low to moderately high Hydrogen Indices (133 to 326) indicate the presence of a gas-prone to oil and gas-prone kerogen facies (Figure 4). Kerogen typing analysis data for these coals indicate the presence of predominantly gas-prone Type III kerogen (Figure 9).

Two oil seep samples recovered from the Lariang region and one oil seep sample from the Karama region have been described as brownish black-coloured liquids at room temperature. Low gravity values (10.60° to 14.80 °API) suggest that these are heavy crudes, probably due to the effects of biodegradation. Low wax contents (0.49-2.03 wt.%) and low sulphur contents (0.15-0.19 wt.%) suggest they were originally sweet crudes. Liquid chromatography data indicates a predominance of saturated hydrocarbons (44.44-54.07 %) with equally significant amounts of aromatic hydrocarbons (39.41-43.80 %).

Biomarker triterpanes fragmentograms (m/z 191) for two oil seeps from the Lariang region display relatively simple distributions of bacterially-derived 17αβ (H)-hopanes. These GC-MS patterns are dominated by the C_{30} αβ (H)-hopane (C_{30} hopane>C_{29} hopane), which suggests the oil seeps are of clastic origin. The oil sample from the Karama region displays a relatively simple distribution of bacterially-derived 17αβ (H)-hopanes, which is dominated by C_{29} αβ (H)-hopane (C_{29} hopane>C_{30} hopane), suggesting the oil seep samples are of algal origin (Figure 10).

The sterane (m/z 217) distributions for the oil seep samples from the Lariang region shows a full suite of normal steranes with the $C_{29}\alpha\alpha\alpha$(R) forms more abundant (55.56-59.18 %) relative to the $C_{27}\alpha\alpha\alpha$(R) steranes (30.61-33.33 %). This implies a significant contribution of herbaceous organic material and minor algal input within the progenitor source rock facies. The sterane distribution of the oil seep from the Karama region shows a full suite of normal steranes with the $C_{27}\alpha\alpha\alpha$(R) forms more abundant (56.76 %) relative to the $C_{29}\alpha\alpha\alpha$(R) steranes (32.43 %), implying a significant contribution of algal-derived organic matter (Figure 10).

Biomarker isomerisation ratios for the three oil seeps (C29ααα 20R to the C29ααα 20S steranes (0.19 to 0.37) and the C29αββ R+S to the ααα S+R steranes (0.28 to 0.47) suggests they were generated at c. 0.60-0.70 %Ro (Alexander, 1986).

Based on the biomarker distribution, it is likely that two oils seeps samples from the Lariang region are derived from a source rock facies containing terrestrial organic matter with some minor algal input. The oil seep sample from the Karama region indicates derivation from a source rock facies containing algal debris mixed with some terrestrial higher plant material. A plot of the sterane distributions on Huang and Meinschein's palaeoenvironment diagram shows that the samples from the Lariang region are situated in the region assigned to oils of "estuarine/shallow lacustrine" environment. The seep from the Karama region falls in the field assigned to "open marine/deep lacustrine".

Screening geochemistry of the cuttings from the KD-1well indicates significant source rock potential in the Early Miocene section. TOC analysis shows poor to good organic richness (0.6-1.99w% TOC). Vitrinite reflectance analysis below 2700 m MD demonstrates thermally mature source rock (0.59% Ro to 0.79% Ro). Potential source rocks are considered have poor to fair hydrocarbon potential based on poor to moderate pyrolysis yield (S1+S2 = 0.64-3.98 mgHC/gm rock). Hydrogen Indices from the Budung-Budung Formation (97 to 375) indicate mainly gas source character with secondary oil-prone kerogen (Figure 9).

Based on the stratigraphy for the Lariang and Karama Regions of the Western Central Sulawesi (Calvert, 2000), the Budung-Budung Formation is characterised by marine sediments. Thus, there is a possibility that the oil is originated from Budung-Budung Formation. However, this statement should be confirmed with further geochemical analysis (oil to source rock correlation analysis).

PETROLEUM SYSTEM IMPLICATIONS

Three potential play types are recognized in the Lariang-Karama area in onshore West Sulawesi.

Play type 1: Fluvio-deltaic sandstones of the Middle Eocene-Kalumpang Formation

Reservoir	:	Eocene Fluvio-deltaic sandstones of the Kalumpang Formation
Trap & seal	:	Structural trap; Eocene intra formational shales and regional shale of Syn-rift
Source Rock	:	Eocene Toraja Group
Timing and Migration	:	Early Miocene to present; migration through carrier beds and faults into the trap.

Play type 2: Marine clastics of the Miocene Lisu Formation

Reservoir	:	Miocene marine clastics (turbidites)
Trap & seal	:	Structural trap; regional shales of the post-rift.
Source Rock	:	Eocene Toraja Group, Miocene Budung-Budung Formation
Timing and Migration	:	Early Miocene to present; migration through carrier beds and faults into the trap.

Play type 3: Carbonate of the Oligocene-Miocene

Reservoir	:	Oligocene-Miocene carbonates
Trap&seal	:	Structural trap; regional shale of the post-rift.
Source Rock	:	Eocene Toraja Group, Miocene Budung-Budung Formation.
Timing and Migration	:	Early Miocene to present; migration through carrier beds and faults into the trap.

Reservoir

The two wells drilled by Tately Budong-Budong N.V. in 2011 confirm the existence of reservoirs within Miocene carbonates and clastics.

Petrographic analysis of SWC samples in LG-1 for the Late Miocene show moderate visible porosity

(<15%) for sandstones and limestones . Carbonate rocks are not well developed in the area at the outcrop, but the presence of hydrocarbons within a Late Miocene limestone in the LG-1 well indicates that carbonate reservoirs may have exploration potential in the Lariang area.

In the KD-1 well, >50 m of sandstone with oil shows was intersected in the Early Miocene section. The sand interval has good visual porosity. Unfortunately, no MDT result were obtained due to tight formation or lost seals. The Tike-1 well in the Lariang area intersected sands 3-15 m thick. Core analysis of the Middle Miocene interval recorded an average porosity of 14.3% with a low permeability (2.24mD). The sands are thinly bedded, frequently silty and unconsolidated (Figure 11).

The outcrops of Eocene fluvio-deltaics in the Karama area indicate good reservoir quality with a thickness ranging from 1-20m and 17% average porosity (Figure 12). Unfortunately, this stratigraphic interval has not yet been penetrated in any of the wells drilled to date. It is still questionable whether Eocene terrestrial facies occur west of the present day mountain front.

Trap and Seal

Basin inversion and the development of a fold thrust belt have created trapping structures throughout the region at all levels within the Tertiary sequence. The intra-formational shales within the Eocene section of the Kalumpang Formation would provide seals for fluvio-deltaic traps and the outer shelf to bathyal shales of the Late Eocene–Mio-Pliocene (Budung-Budung and Lisu Formations) would provide good regional top seals for higher level traps.

Timing and Migration

The top of the predicted oil window (0.6% Ro) is modeled within the Early Miocene section in the KD-1 well (Figure 13). Hydrocarbons generated within the Tertiary section may have migrated into anticlinal traps produced by thrusting and inversion. Migration is believed to be facilitated by interconnected fluvial and shallow marine sands.

Source Rock

There are two potential source rocks identified in the area:

Eocene Kalumpang Formation

The samples of the Middle Eocene coals indicate very high organic richness (TOC 54.88-84.2 wt%) and excellent hydrocarbon potential yield (S1+S1 103.56-228.87mg HC/gm rock). Low to moderately high Hydrogen Indices (133 to 326) indicate the presence of gas-prone to oil and gas-prone kerogen facies. Kerogen typing analysis indicates that the coals at outcrop are predominantly gas-prone.

The GC-MS biomarker data of two oil seeps from the Lariang area were generated from an organic assemblage dominated by terrestrial higher plant material with some algal input.

Miocene Budung-Budung Formation

The TOC of samples from the Early Miocene section of the KD-1 well shows poor to good organic richness (0.6-1.99w% TOC), poor to moderate potential yield (S1+S2 = 0.64-3.98 mgHC/gm rock), Hydrogen Indices ranging from 97-375 indicating a mainly gas source character with secondary oil-prone kerogen.

An oil seep the from Karama area (ST 7.3) indicates derivation from a source rock facies containing algal debris mixed with some terrestrial higher plant material. A plot of the sterane distribution shows that the seep falls in to open marine/deep lacustrine environment.

SUMMARY

West Sulawesi and its environs is reasonably well studied. However, a recent review of unpublished reports, the examination of new data sets (onshore seismic and well data) and the collection of a new sample set has allowed current models to be tested and the petroleum system to be explained. This recent work supports an extensional model with syn and post-rift phases initiated in the Middle Eocene and continuing into the Early Pliocene, with contraction and basin inversion in Late Pliocene/Pleistocene times. This late contraction led to structural trap development for the maturing petroleum system hydrocarbons to migrate into. Late strike slip motion on faults that cut across the coastal basins and continue into the offshore area contribute in part to the rapid uplift and deposition of thick, coarse clastic sequences in the coastal basins. Contraction on a NW-SE axis also causes regional uplift and the interaction of a NW-transported but compartmentalized thrust belt which gives rise to inversion in the coastal plain as the thrust fronts pass through the region. This also contributes to rapid changes in sedimentary facies within each basin.

The Lariang and Karama areas demonstrate an active working petroleum system. Oil is present and the late Plio-Pleistocene contractional episode has produced numerous anticlinal traps. Migration of oil occurred within the tertiary to the present so filling the traps is not an issue. Regional seals are also present. Further evaluation of the sand fairways during the Miocene period will be critical for any future exploration program.

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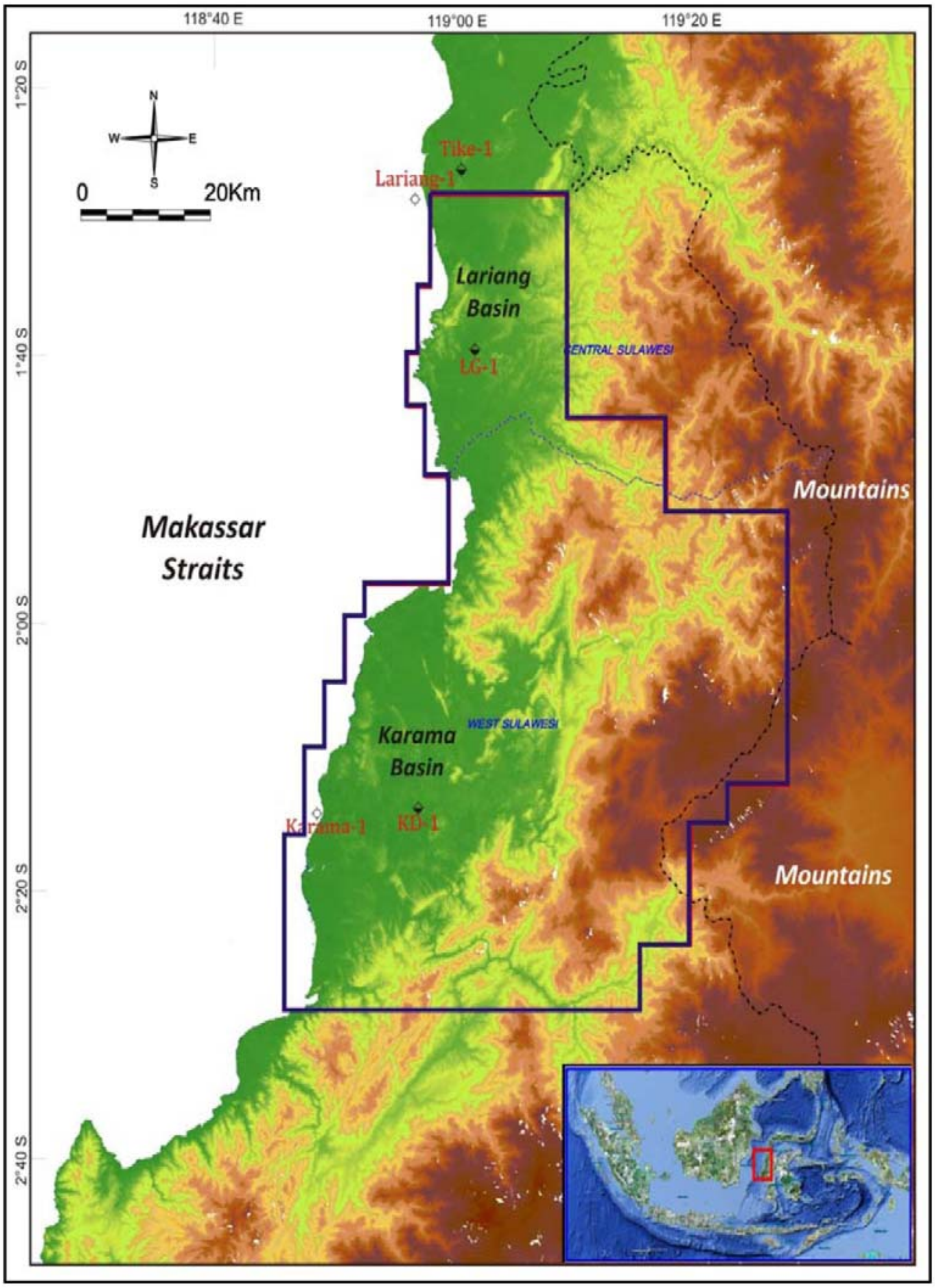

Figure 1 – Location Map and Geomorphology of the Region

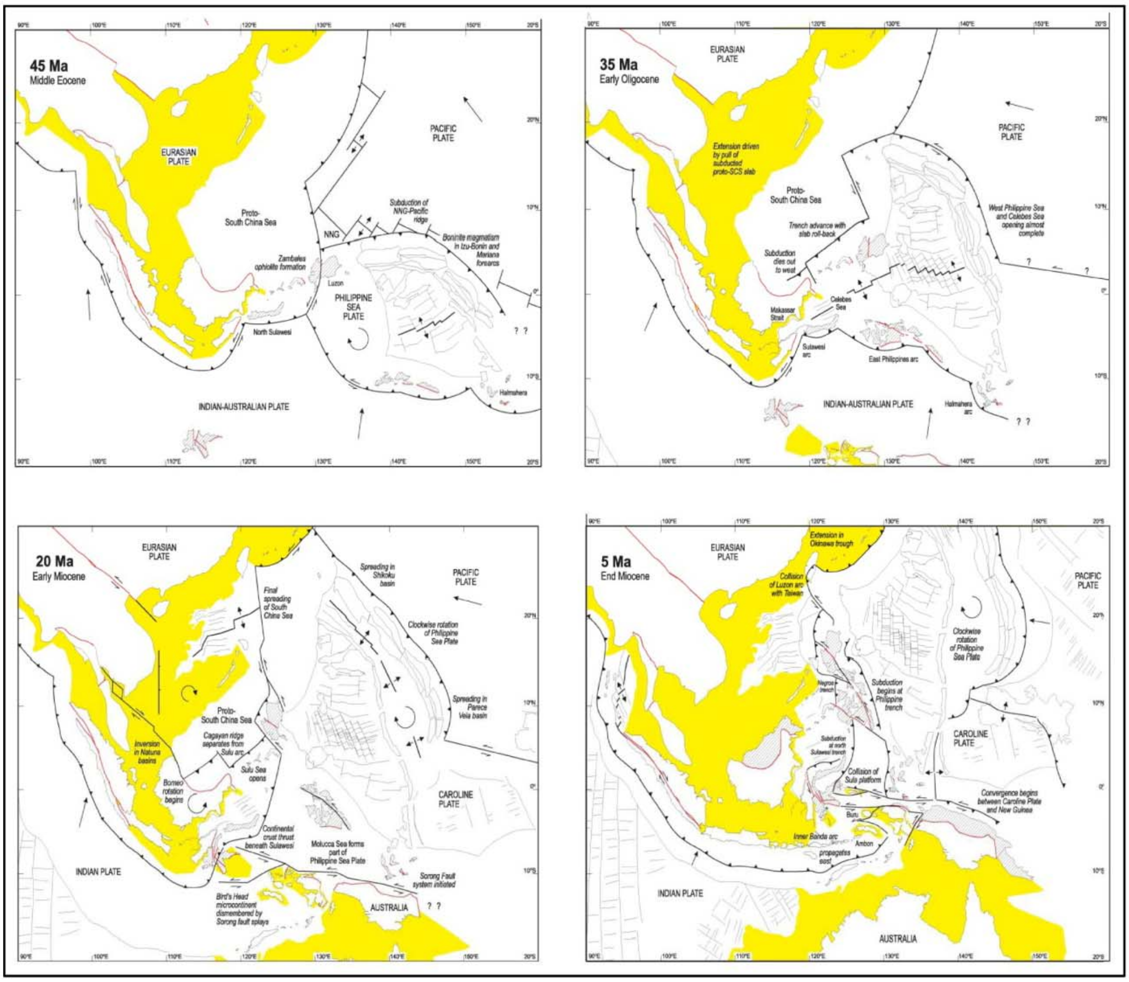

Figure 2 - Tertiary regional plate-tectonic setting (after Hall, 1996)

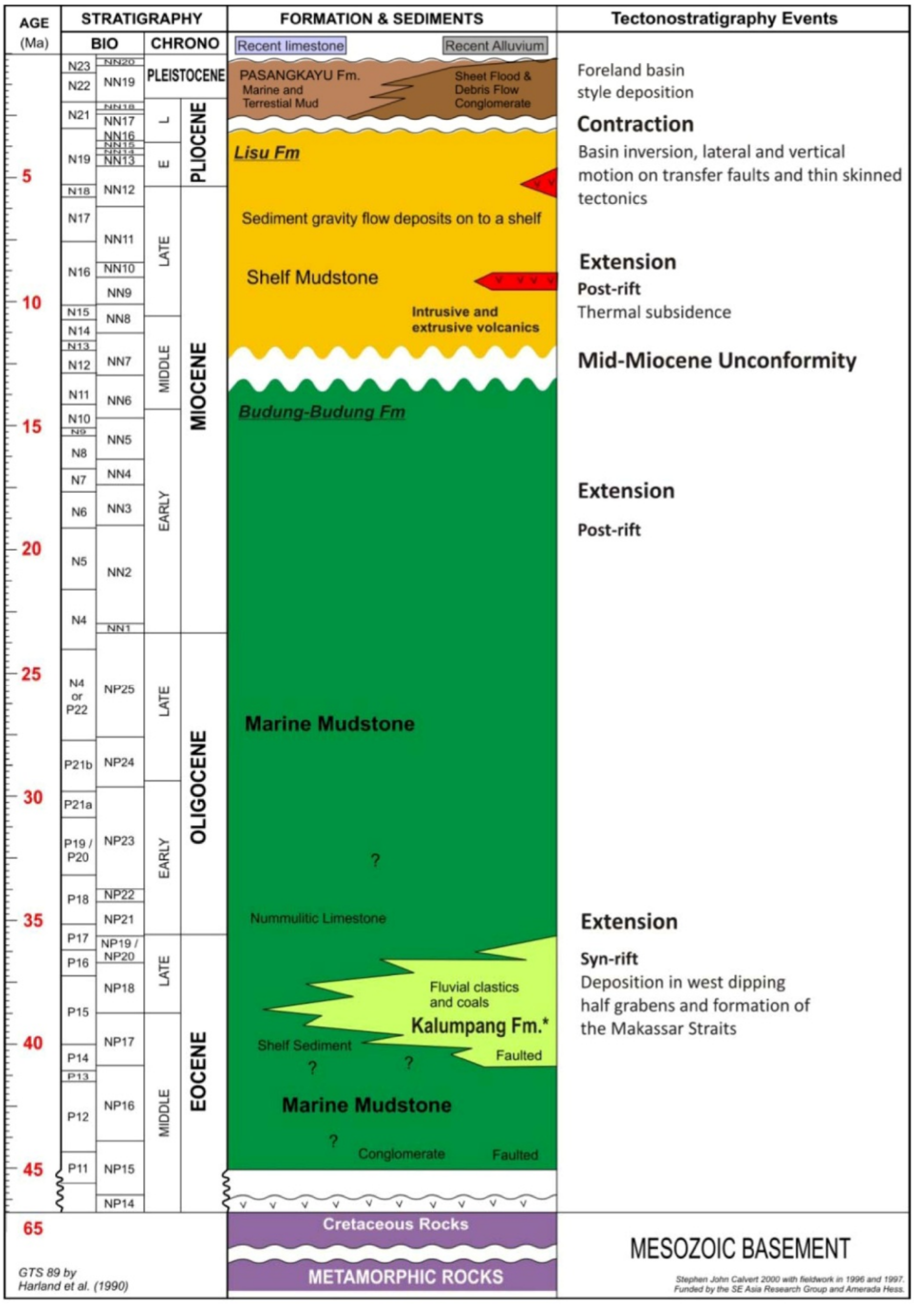

Figure 3 – Stratigraphy of the Karama and Lariang Basin (after Calvert 2000)

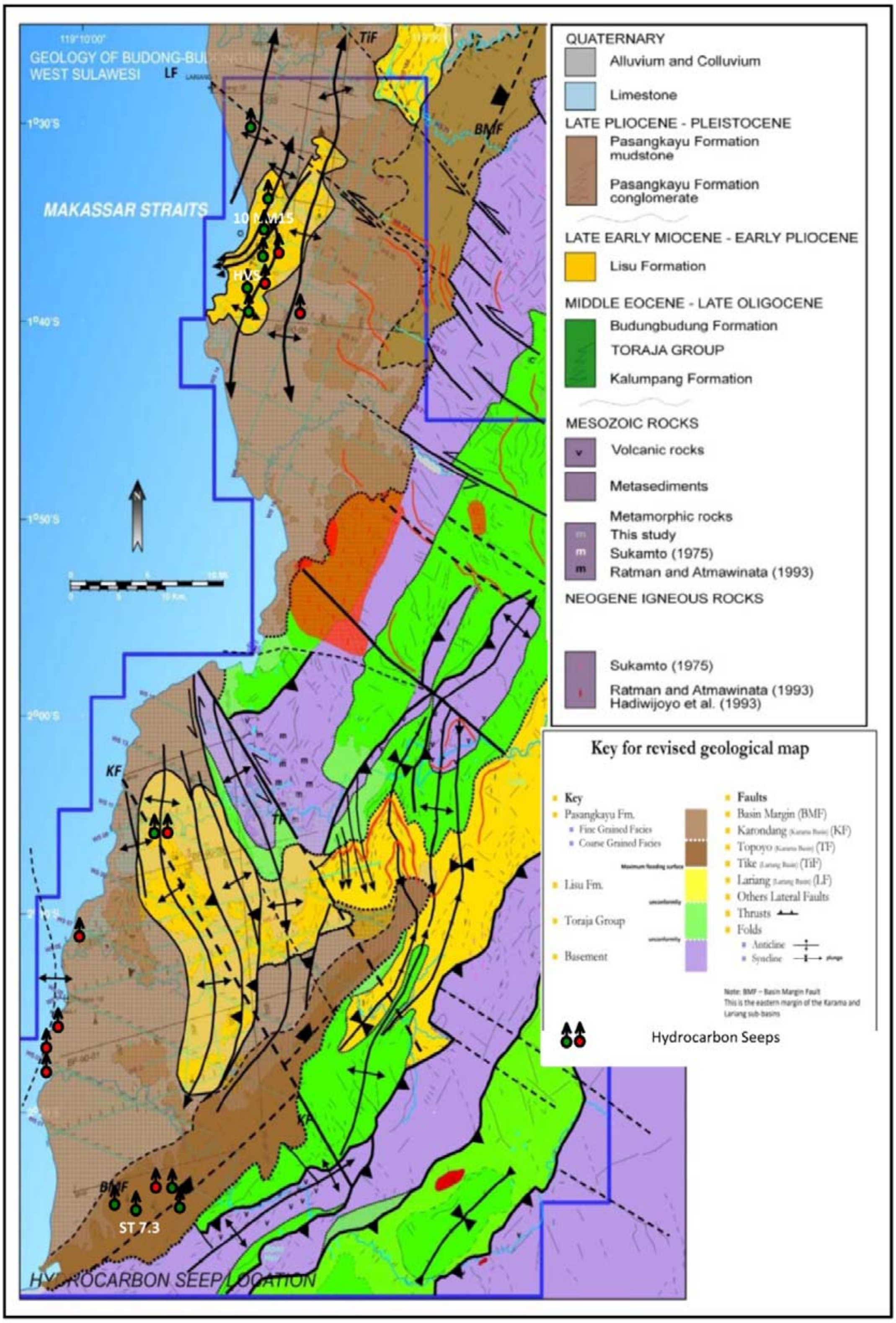

Figure 4 – Geology Map Emphasizing Structural Pattern (based on Calvert 2000, Chamberlain and Seago 1995 and Seago 2009)

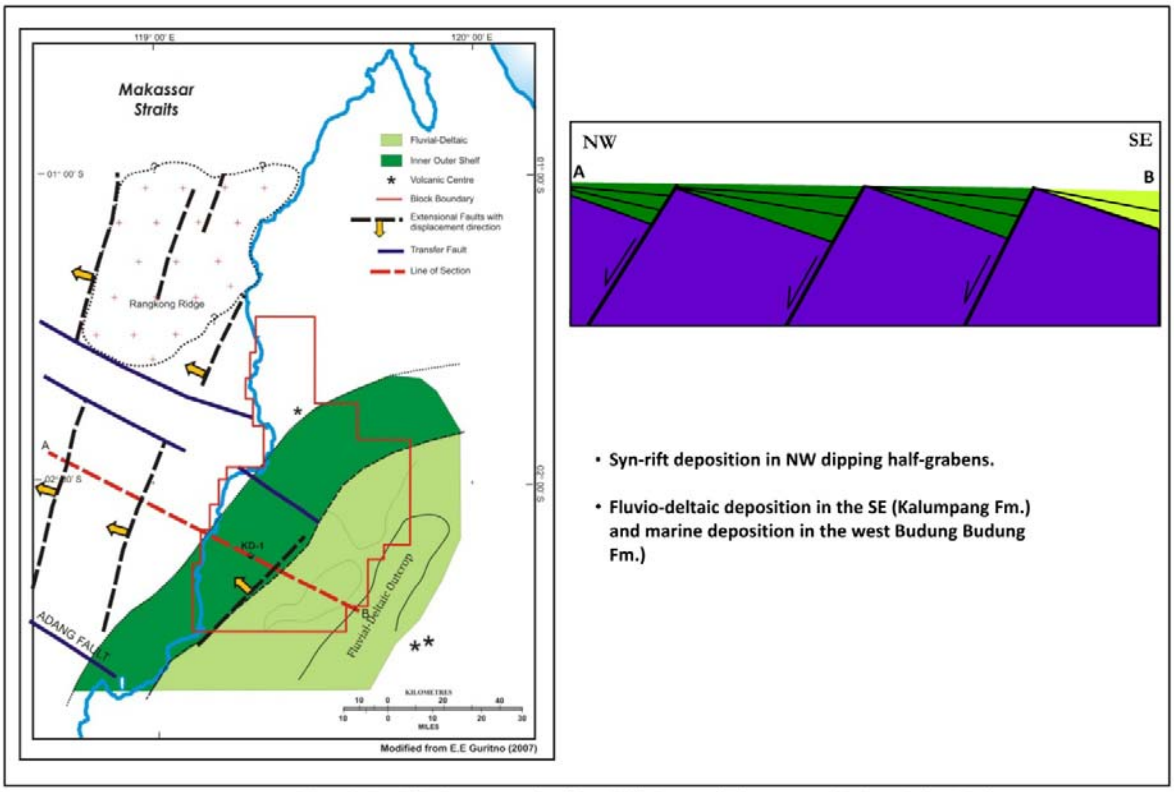

Figure 5 – Syn-rift Palaeogeography of the Middle Eocene (Kalumpang and Budung Budung Fms)

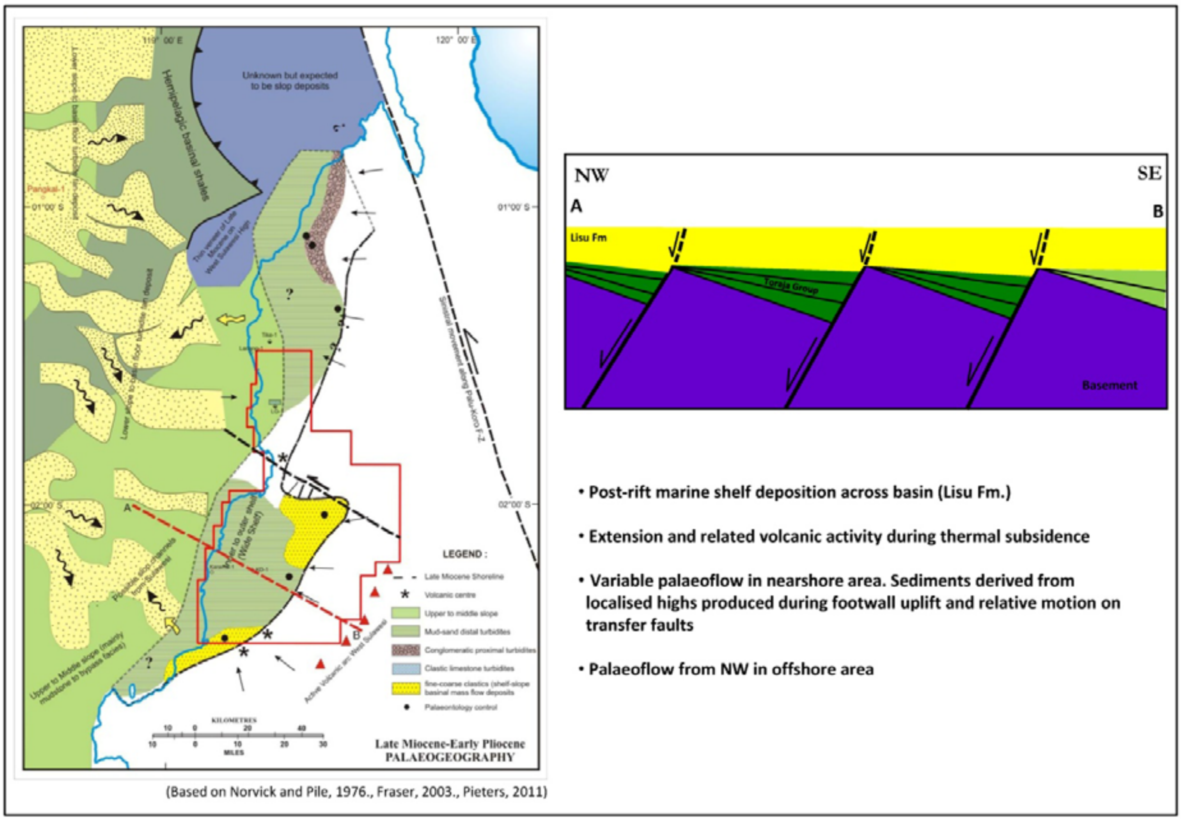

Figure 6 – Post-rift Palaeogeography of the Late Miocene-Early Pliocene (Lisu Fm.)

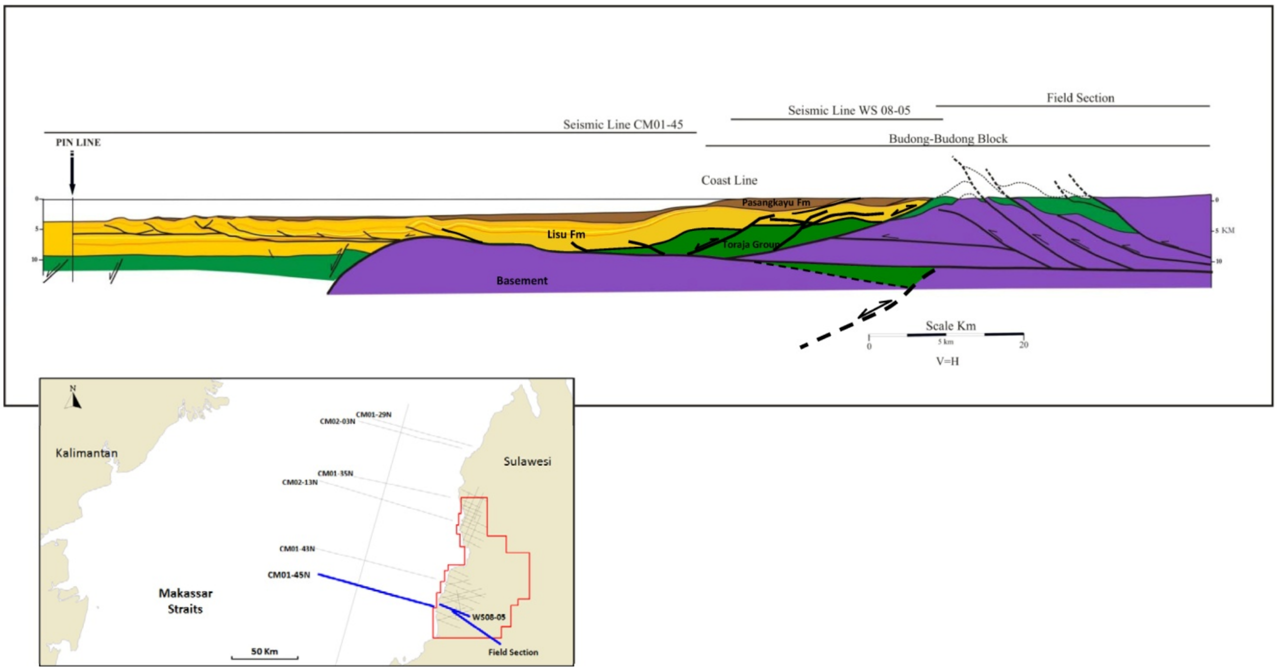

Figure 7 – Composite Balance Cross Section Across West Sulawesi using field, onshore Seismic and offshore Seismic Data

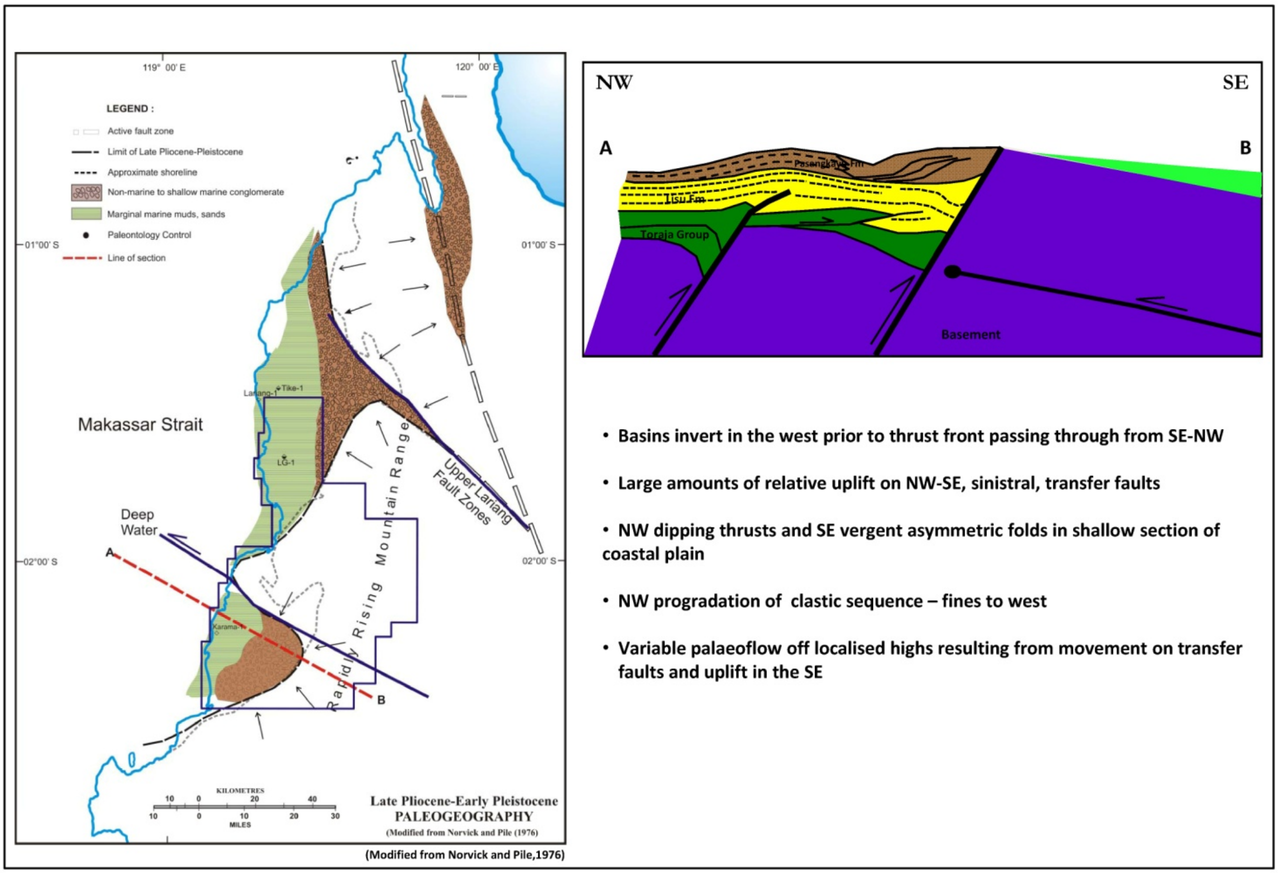

Figure 8 – Palaeogeography of the Plio-Pleistocene (Pasangkayu Formation)

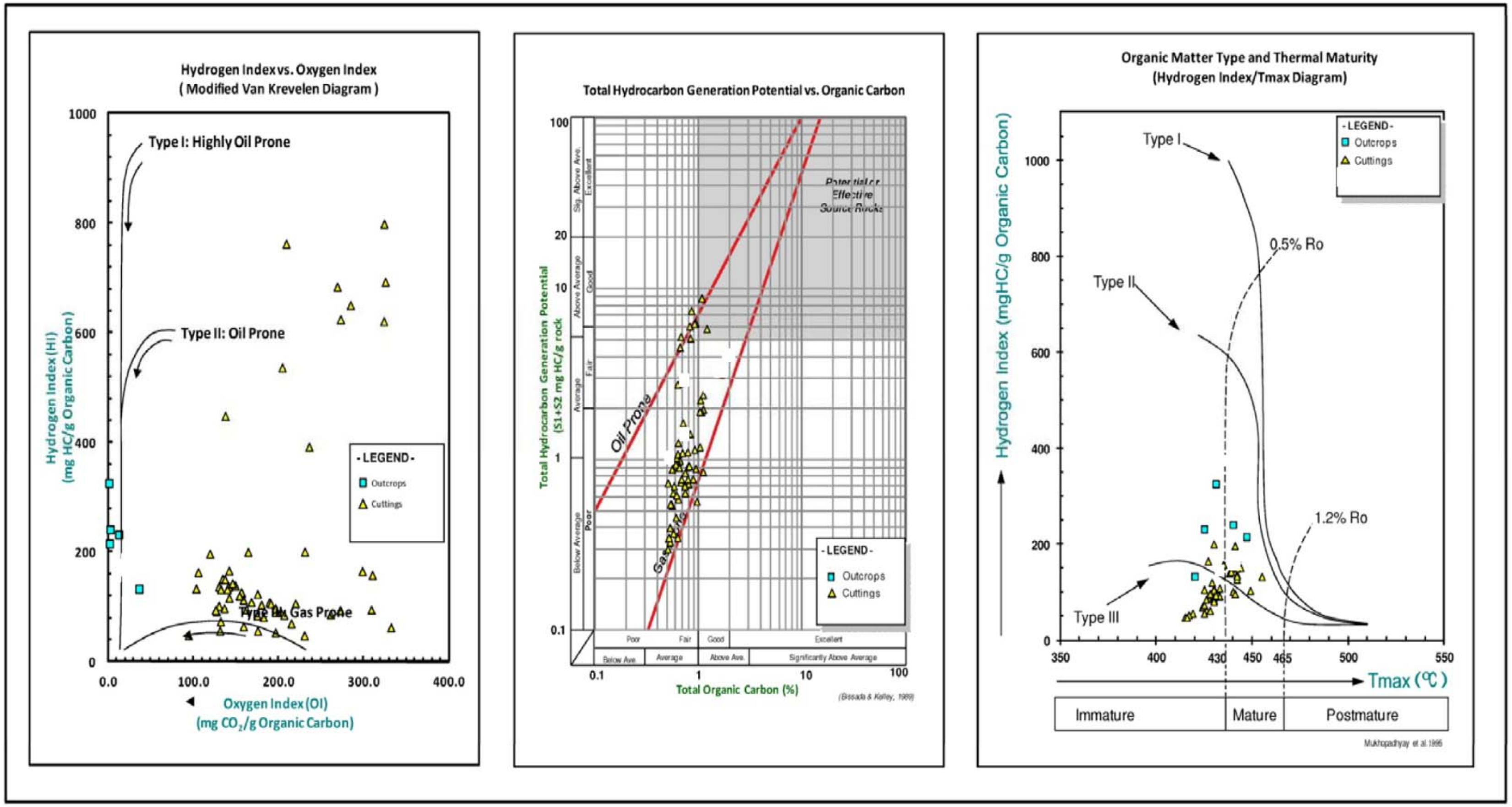

Figure 9 – Potential Source Rock from Coal Outcrop and Cuttings Data

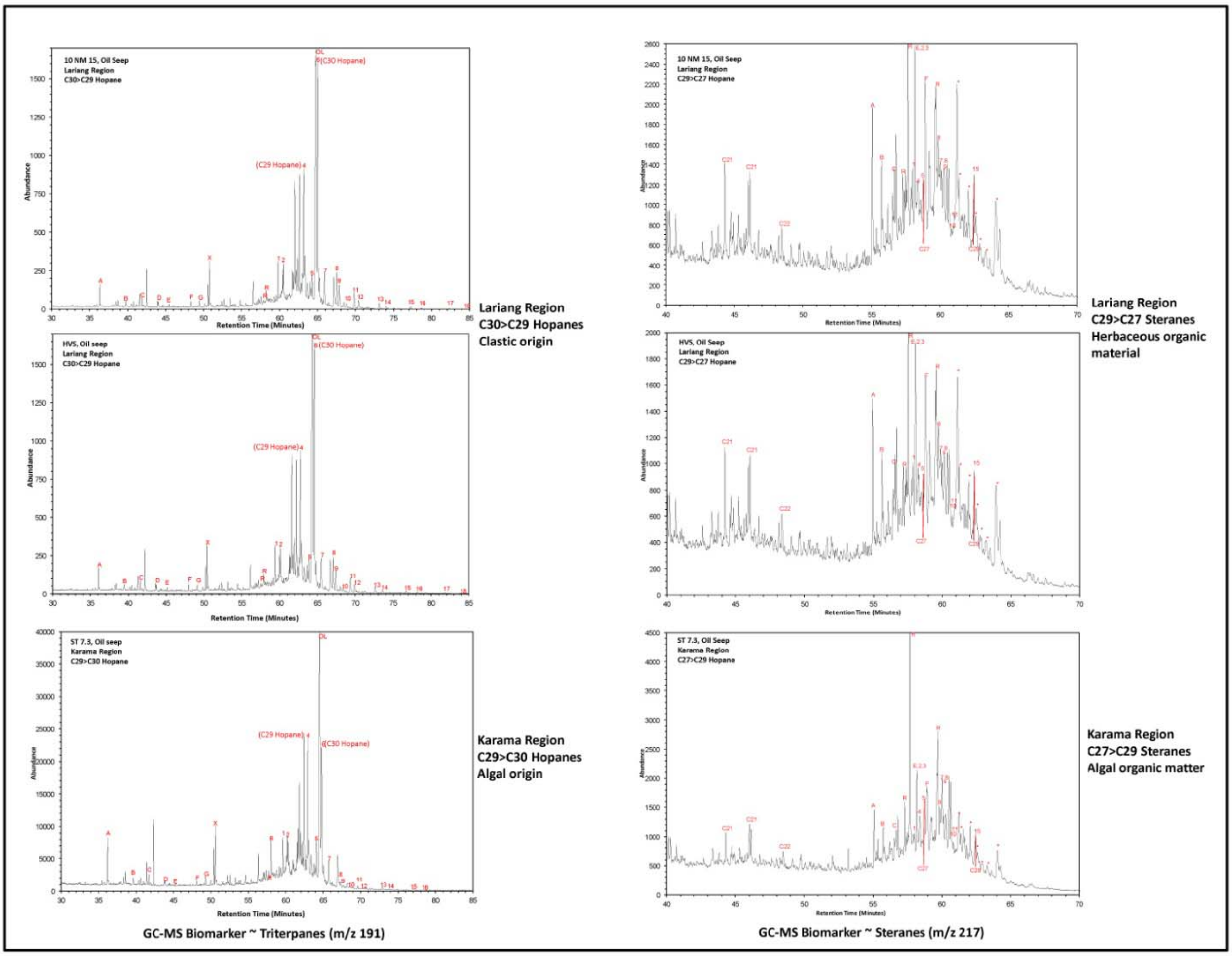

Figure 10 - GC-MS Biomarker Triterpane (mz 191) and Sterane (mz 217)

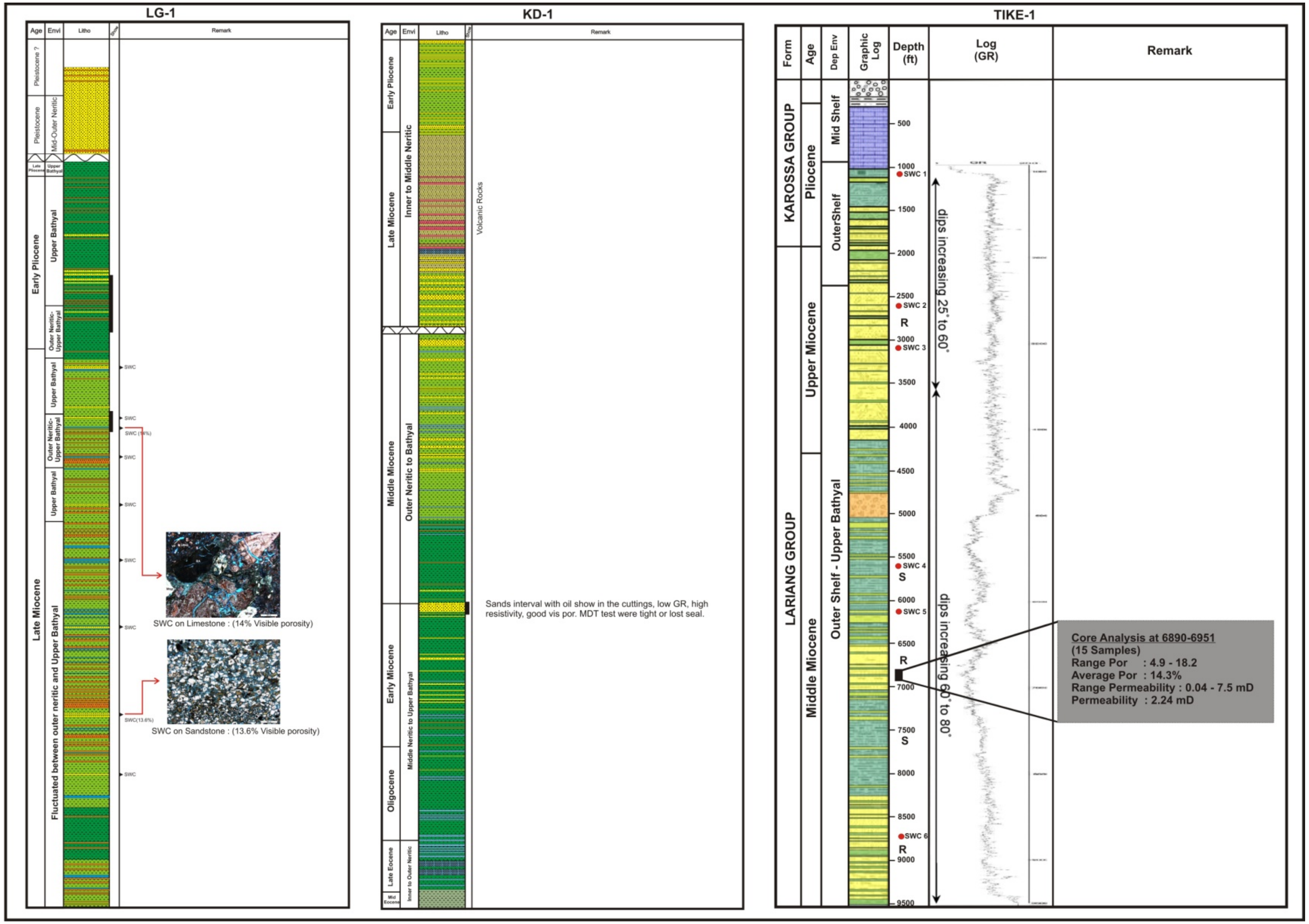

Figure 11 - Miocene reservoir Quality

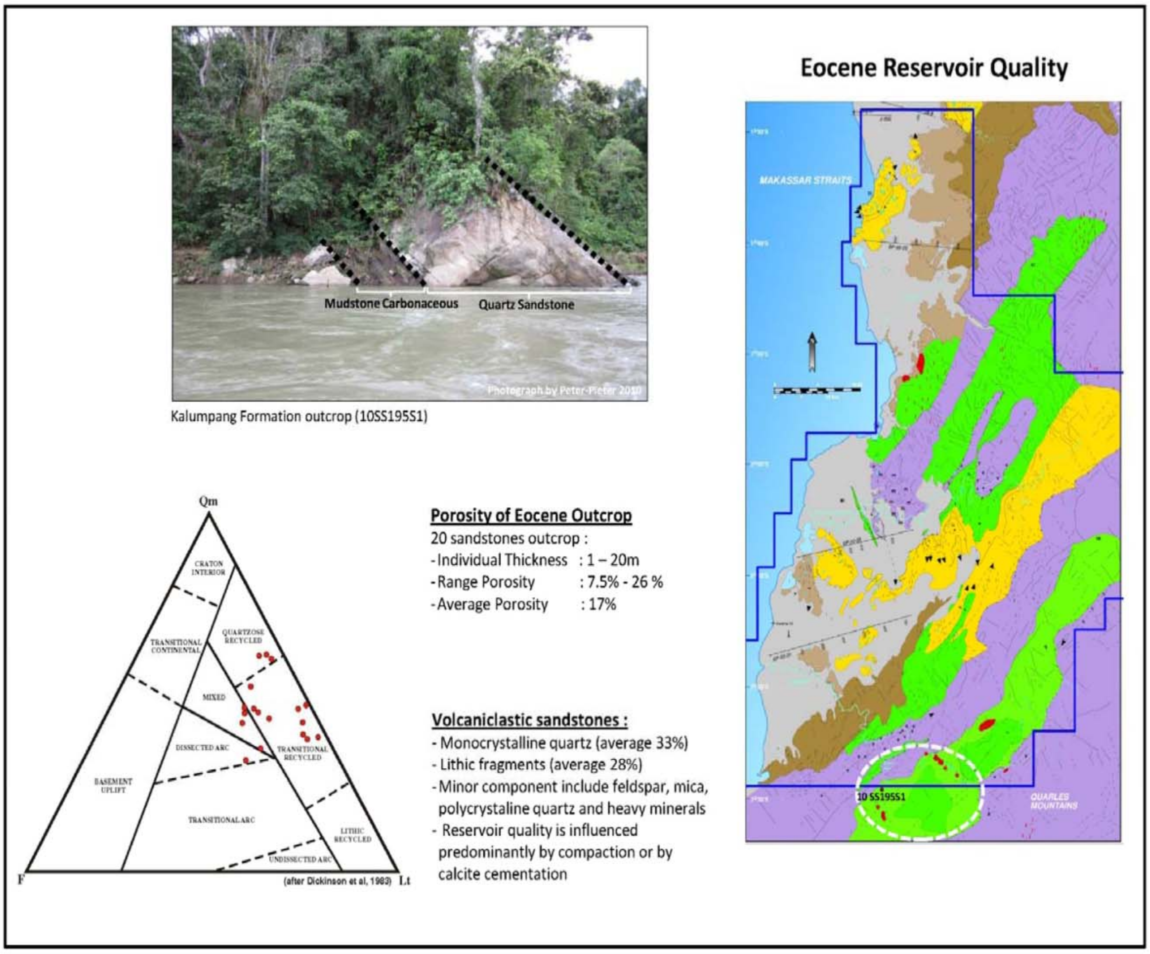

Figure 12 – Eocene Reservoir Quality from Outcrop Data

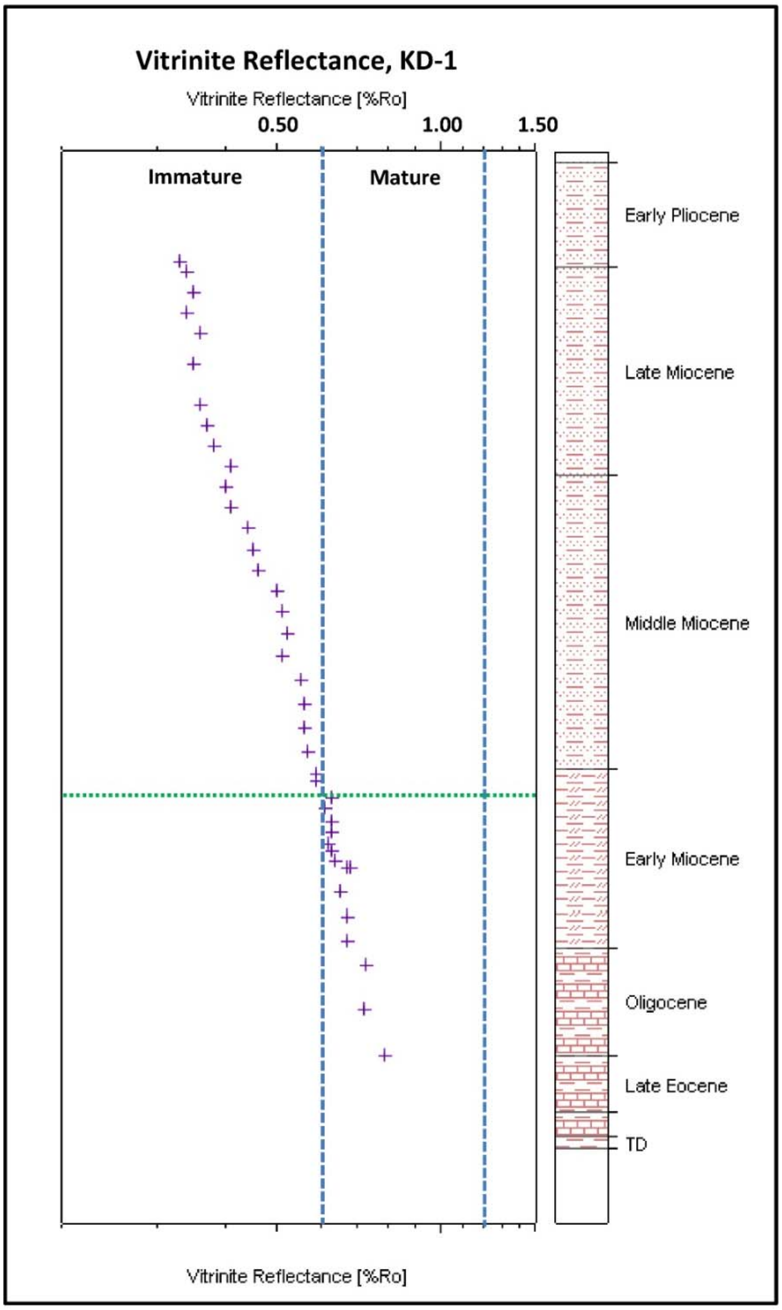

Figure 13 - Thermal Maturity Profile of KD-1 Well