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FLUVIAL-TO-DEEPWATER STRATIGRAPHY AND STRUCTURAL DEVELOPMENT OF THE SOUTHERN PART OF NORTH MAKASSAR BASIN, INDONESIA

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ABSTRACT

The deposition sequence in the southern part of the North Makassar Basin began with non-marine fluvio-deltaic-lacustrine syn-rift deposits of Early Eocene. This sequence is marked with a series of horst and graben structures interpreted to occur during the extensional tectonic phase of the region.

The non-marine sequences were immediately conformable overlain by a deepwater depositional system across the region, with an exception of the Paternoster Platform area. In this platform area, the Eocene sequence was partially uplifted and eroded in the Early Oligocene which resulted in the initiation of shallow marine carbonate depositions. Part of this region became favorable for carbonate reefs to grow. This shallow marine deposition is continuous until the present day.

In contrast, in the deeper part of the basin to the northeast, deepwater depositions continuously occurred since the Early Oligocene until the present day. The stratigraphic contact between the Eocene non-marine and Oligocene deepwater sequences is generally difficult to differentiate seismically and thus become stratigraphically conformable though there is still major change genetically in depositional sequence. The Paternoster Platform uplift and erosion in the Early Oligocene was followed by the beginning of the Adang Fault activity, showing a major normal fault component dipping to the northeast.

In the Middle Miocene, the Sepinggan delta eastward progradation sequence commenced. In the outer shelf break area of the delta, the clastic delta sequence sediments were partially mixed with some carbonate materials derived from the Paternoster Platform in the southwest where the platform edge were severely inverted and uplifted. The delta is poorly developed, has limited extent, and is interpreted to cease in the early Late Miocene at the time of marine flooding.

There are three petroleum systems with various exploration plays present in the southern part of the North Makassar Basin. To the southwest, the deltaic sand play of Sepinggan delta and transgressive carbonate platform play with some minor patch reefs. Towards deep basin in the northeast, deepwater carbonate debris and biogenic gas plays are believed to be well-developed.

INTRODUCTION

North Makassar Basin is located in the offshore area of the Makassar Strait between the islands of Kalimantan and Sulawesi. Water depth ranges from less than 100 m to 2,250 m towards the east near the offshore Western Sulawesi.

The basin is one of the well-known basins in the country due to the presence of the Mahakam delta which is very prolific and has many large gas fields. Immediately to the east of the basin beyond the present day shelf slope break bathymetry, several large gas fields have also been discovered in deepwater (Figure 1). However, the southern part of the basin remains challenging to explore, as the deepwater portion in this part of the basin has a lack of geological information because it is still relatively under-explored stage.

Geologically, the basin is located in the southeastern margin of Sundaland Craton (Figure 2). The western and southern edges of the craton are characterized by intense seismicity and volcanism resulting from Cenozoic subduction between the Eurasian continental and the Indian oceanic plates. The craton is generally free of seismicity and volcanism, and is described as a tectonically quiet region (Hall, 2009).

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To the south, the basin is bounded by the northern edge of the Paternoster Platform. The basin is bounded to the west by East Kalimantan where the Mahakam Delta is present with numerous large gas discoveries. Offshore West Sulawesi is the eastern edge of the basin where deepwater deposition continuously takes place. The connection between the North Makassar and South Makassar Basins is a narrow deep basin setting between East Kalimantan and West Sulawesi.

This paper discusses the fluvial-to-deepwater depositional stratigraphy and structural development of the Cenozoic in the southern part of the North Makassar Basin covering the areas of the coastal plain in the west to the deepwater setting in the east.

STRATIGRAPHY

The deposition in the southern part of the North Makassar basin began with non-marine syn-rift sedimentation in Early Eocene (Figures 3A and 3B). It is believed that the Eocene section lies directly on top of basement, although the top basement itself is generally difficult to define seismically. The two recent wells drilled in the region: Rangkong-1 (ExxonMobil, 2009) with total depth (TD) of 14,711 feet and Kaluku-1 (ConocoPhillips, 2011) with TD of 17,359 feet, encountered a considerable thickness of Eocene clastic sequences with TD in the horst structure of basements (Satyana, 2015). This is consistent with the seismic interpretation showing a series of the formation of local horsts and grabens in the Eocene section.

A volcanic basaltic igneous basement with a porphyritic texture was observed in Rangkong-1 (Satyana, 2015). The geochemistry of the rock suggests that these are andesites contaminated by continental crust. In Kaluku-1, the well penetrated a volcanic tuff dated as Late Cretaceous, Maastrichtian in age (Satyana, 2015).

The depositional model of the syn-rift and early post-rift sequences is shown in Figure 4. The deposition began with an initial fill of predominantly continental deposits of coarse alluvial and fluvial facies, and predominantly shales of the lacustrine facies as the first cycle component, while toward seawards to the northeast there are marginal marine and sediment starved shallow marine to highly sediment starved deeper water rift. The coarse non-marine clastics are likely to occur at the basin margins only. The deposition gradually became shallow marine deposits across the whole southwestern part of the North Makassar Basin and remained deeper towards northeast. The starved deepwater syn-rift setting might not develop in the region as indicated by drilling results of the most recent wells. However, with the exception of the local rift highs, the center of the rift could become marine and preference for carbonate deposition.

Similarly, in the early post-rift section to the southwest, the continental clastics and shallow marine sediments are likely to be present. The sediments are shallow marine-carbonate dominated, with carbonate build-ups; and gradually changed to deeper marine-carbonate and shales in the area further to the northeast. A minor unconformity could occur in the Late Eocene at the time of horst-graben structuring developed following the end of the syn-rift deposition of the Tanjung Formation. This inversion could be a minor uplift and erosion as interpreted in some seismic lines located in the southwestern part of the region.

Satyana (2015) reported that a 500-foot sequence of massive homogeneous Eocene shales was encountered in Kaluku-1 well with a 27-foot interval of argillaceous limestones at the base of the shales. The well also penetrated interbeds of shales, thin limestones, and occasional thin but clean sands with an excellent reservoir character. The depositional environment of the sequences from the top of basement to the shallower sections gradually changes from deep lacustrine to transition – inner to shallow neritic, and becomes lower coastal plain to outer neritic. The section has been dated as Eocene (Figure 5). Live but very waxy oil with an API gravity of 25.5^0 and 29.6^0 at 60^0 F was recovered in wireline chambers. The oil has a pour point of 113^0 F, sulfur content of 0.102 % wt, and a wax content of 17.23 % wt (Figure 6).

After the Eocene rifting phase, post-rift subsidence or sag took place in the Oligocene which resulted in the deposition of deepwater sediments towards northeast. During this epoch, thin deepwater sequences were deposited in this northeastern area as penetrated by Kaluku-1 well. Seismically, the contact between the Eocene syn-rift and Oligocene early post-rift sequences in this part of the region is not possible to define clearly due to no obvious contrast impedance and sparse seismic grid.

The Adang Fault could be initiated following the uplift of the Paternoster Platform in the Early Oligocene. It is believed that the fault began with a normal dip down-thrown to the northeast. The upper bathyal deepwater shales and some very fine grained clastics of carbonate debris become the dominant lithology to the northeast in the deepwater setting of the southern part of the basin. The sediment provenance is likely to be the reefal and platform carbonates developed on the Paternoster Platform. The transgression impact extended over most of the local highs including the Paternoster Platform, which became the site for development of the reefs of the Berai Formation (Pireno et al., 2009).

In the Early Miocene, development of the Oligocene Berai reefal carbonates was terminated by the middle to outer neritic clastics of the Lower Warukin Formation (Figure 3B) or shallow marine deposits of the Pamaluan and Bebulu Formations. The provenance of these clastics could be from Central Kalimantan.

Seismic interpretation and structural restoration suggest that major inversion and uplift of the Paternoster Platform is interpreted to occur in the Middle Miocene (Figure 7) at the time of the regional unconformity. This second major unconformity occurred in the Early to Middle Miocene has been observed by Kupecz et al. (2013) in the Pangkat Graben in the southern flank of the Paternoster Platform. Late Middle Miocene unconformity surface has been interpreted by Malecek and Lunt (1995) in the offshore East Kalimantan. Part of the Oligocene carbonates on the platform and its flank were severely eroded at this time, but the deepwater sediments remain conformably deposited in the deeper basin to the northeast.

It should be noted that in the northeastern area of the region, the upper bathyal deepwater sequences remain thin and condensed as shown in Kaluku-1 well (Figures 3B and 5). This part of the basin could have been starved for a long time period since the Late Eocene to Early Miocene.

In the southern flank of the Paternoster platform, the erosion resulted in conglomeratic to brecciated appearance of the carbonates consistent with a talus deposit at the base of the slope at the foot of the platform (Pireno et al., 2009). This analog might be applicable to the northern flank deposition of the platform, the conglomeratic to brecciated deposits could be present.

Immediately following the major uplift in the Middle Miocene, the Upper Warukin Formation reef development was unconformably deposited over the Paternoster Platform region. Towards the northeast, the mega-sequence of deepwater clastics has been continuously deposited (Figures 3B and 5).

Immediately to the northwest of the Paternoster Platform flank, there was a regressive, prograding delta called the Sepinggan delta. Loiret and Mugniot (1982) interpreted the deposition of Sepinggan deltaic sequence occurred in the Middle Miocene. The sequence consists of alternation of sandstones, shales and coals. The sediment provenance of this delta is older sequence of sediments located onshore East Kalimantan to the west (Syarifuddin et al., 2008; and Dal et al., 2012). This prograding delta is approximately equivalent to the Balikpapan Beds. A local erosional unconformity defined by seismic marker at the top of the delta deposits is present in the onshore area further to the west, but it is difficult to define this surface offshore to the east. The delta is overlain by a marine transgression that generated thick sequence of the shelfal carbonates, including some reefal and interbeds of argillaceous sequences that took place in the early Late Miocene, covering the whole platform region.

Further to the northeast, the deepwater deposition is continuous until the present day. The water depth is relatively consistent as an upper bathyal (Figures 3B and 5). At present, the water depth is around 2,200 m. Hence, the deepwater debris sand sheets, channels, and lobes could be present. High resolution of 3D seismic is required to better image the features. Seismic amplitude study could be applicable to define the hydrocarbon presence and distribution.

STRUCTURAL DEVELOPMENT

In the late Early Eocene, approximately 47 mya, the Celebes seafloor spreading initiated in the area immediately to the north of the Makassar Strait which was believed to extend towards the southwest into the North Makassar Basin along the lines of weakness within the Early Eocene sediments (Baillie et al., 2004; Nur'aini et al., 2005; and Puspita et al., 2005). This concept has become the beginning of considerable debate of the basin formation for many years. Similarly, Malecek et al. (1993) proposed that the Kutei/Makassar Strait Basin is a remnant of an oceanic basin of Late Cretaceous age, trapped between the relict subduction zones of northwest Borneo and western Sulawesi. The nature of the crust beneath the basin has been controversial with no agreement about the basement type (Guntoro, 1999; and Hall et al., 2009). However, following the results of the most recent exploration wells drilled in the region, after almost thirty years of uncertainty it is now concluded that the underlying basement of the basin is continental crust (Nainggolan et al., 2015; and Satyana, 2015).

It is believed that the North and South Makassar Basins were originally affected by the subduction of the Australian Plate and the Sunda Craton, which resulted in the development of Early-Middle Eocene large back-arc basins. Beneath the South Makassar Basin is definitively continental crust, based on drilling results and formation of the wells at total depth; and crustal mapping (Bacheller III et al., 2011) (Figures 8A and 8B). One of them is Rangkong-1 drilled with total depth in the basement horst of comprising volcanic basaltic igneous rock.

In the southern part of the North Makassar Basin particularly in the area of northeastern Paternoster Platform, the structural faults are generally grouped into two parts: normal faults in the Eocene section, and fold and thrust faults in the post-Eocene specifically in the Plio-Pleistocene as the Sulawesi Fold and Thrust Belt (Sulawesi FTB) (Figure 9). The normal faults mark the Eocene rift tectonics resulting in a series of structural horsts and grabens. In some areas, the faults are difficult to recognize due to relatively poor seismic quality. To the east towards offshore Western Sulawesi, the horsts and grabens remain preserved, but are strongly uplifted following the uplift and compression of Western Sulawesi in the Plio-Pleistocene times.

Although the thrust faults are much younger than the normal faults, both types of the faults are generally active independently in "their own stratigraphic intervals" and thus both do not influence one another. This has been observed in seismic lines (Figure 7), and is also described in various published papers (Nur'aini et al, 2005; Puspita et al, 2005; and del Negro et al, 2013). However, the reactivation or rejuvenation of the Eocene normal faults could occur during compression and uplift in the Plio-Pleistocene, but it appears they do not significantly impact the overlying sections. Hence, the faults do not cut the Oligocene-Miocene deepwater shale interval. Consequently, the original Late Eocene horst and graben structures remain preserved.

Towards the easternmost area near the western part of offshore Sulawesi, to some degree the Eocene faults might have conceptually been rejuvenated and reactivated, though it is difficult to confirm due to very poor seismic quality. The nearby wells indicate that the rocks within the Eocene mega-sequence are much more rigid. They contain sandstones interbedded with a mix of silty claystones and coal stringers deposited in a lacustrine-fluvio-deltaic setting. On the other hand, the whole post-Eocene mega-sequence consists of mostly deep-marine shales preferential to fold rather than to fault.

The Plio-Pleistocene thrust faults are interpreted to have not been gone into the deeper Eocene section. The faults die out into the thick, Late Miocene marine deepwater shales. It appears that the compressional tectonics and uplift occurred during the Plio-Pleistocene do not have significant impact on the Eocene horst and graben structures in the area (also refer to seismic interpretation by Nur'aini et al., 2005; and del Negro et al., 2013) (Figure 9). The shales are interpreted to be responsible to absorb the Plio-Pleistocene compressional force-stress-strain and to partially slide the fault, if necessary, as a decollement surface.

The major differences in the rock composition content and its plasticity in both Eocene and post-Eocene mega-sequences is interpreted to become one of the key drivers as to whether or not the Plio-Pleistocene thrust fault development extends and cuts into the deeper Eocene section. This is proven by the structure present immediately to the north where numerous severe thrust faults are well-developed which has resulted in a Neogene thin-skinned tectonic type of mega-structure lying above the Eocene section (ex-Statoil Karama Block in 2012). Towards the south this thrust and fold structure cluster is poorly developed and effectively diminishes.

The southern boundary of the North Makassar Basin is bounded by the northern edge of the Paternoster Platform with the northwest-southeast orientated Adang Fault showing a dextral movement component (Nainggolan et al, 2015). This fault is believed to become an important feature controlling the structure and stratigraphy of the region during the Neogene. The age of the fault is difficult to determine due to poor data quality, however, the seismic interpretation and paleogeographic reconstruction suggest that this fault could have been initiated in the Early Oligocene, with the major normal fault component dipping relatively to the northeast. The Eocene non-marine sequence was faulted and pushed away to the north towards the deeper part of the basin (Figures 3A and 3B).

The Oligocene carbonates on the Paternoster Platform are shallow marine, while in contrast the same age sediments immediately to the southern basin margin on the northern flank of the platform and in laterally stratigraphic contact position, are all deepwater in nature. Similarly, immediately towards the west onshore eastern Kalimantan, during the stratigraphic record of the early phase of development of the Kutai and Barito Basins, the lithofacies either side of the Adang Fault are broadly similar. By the Early Oligocene, however, a sharp break in paleo-water depth is recorded, which is interpreted to be an indication of normal faulting with down-throw to the north (Witts et al., 2015) (Figure 10). Further to the west onshore, Susianto et al. (2012) interpreted the fault as complex segments with various fault splays.

The structural restoration and paleogeographic reconstruction indicate that a major tilting of the basin likely occurred in the Middle Miocene. While the basin margin in the southwest was being uplifted, the basin center in the northeast developed more subsidence (Figures 7 and 11). The Oligocene paleo-water depth could be as deep as upper bathyal, as indicated in Kaluku-1. The mechanism of this inversion remains unknown. However, it is possible that an oblique angle of the stress-strain mode towards the platform took place, resulting in the inversion and reactivation of the Adang Fault to be in a dextral strike-slip mode. This is still a speculative thought on how the fault began to deform in a strike-slip movement in the Middle Miocene (Figure 3B). Further data acquisition is required to confirm this, since there are no hard data available at the moment to clearly support this concept.

PETROLEUM IMPLICATION AND EXPLORATION PLAY

As the basement type beneath the North Makassar Basin is now proven to be continental crust, the petroleum system in the basin becomes more obvious. The syn-rift source rocks that were previously in question now become more attractive specifically following the success of recovered oil and significant hydrocarbon shows in the most recent wells. Satyana (2015) successfully published crucial information of the well results which is not only to establish the presence of continental crust, but also to prove the presence of hydrocarbon in the region.

Based on the petroleum system types (PSTs) of Doust and Sumner (2007) shown in Figure 12, it appears that there are three (3) active petroleum systems that might be present in the southern part of the North Makassar Basin. The first main petroleum system is an early syn-rift lacustrine petroleum system (type 1, oil prone). This is the Eocene Tanjung non-marine syn-rift deposited immediately above the basement (Figures 3B, 4, and 13-14). The second petroleum system is likely to be in the Oligo-Miocene (type 4, oil/gas prone), which comprises the late post-rift reefal carbonate and regressive deltaic petroleum system. This closely corresponds with the development of the Sepinggan delta; and Berai and Upper Warukin Carbonates (Figures 3B and 13-14). The third petroleum system is related to the deepwater depositional settings located to the northeastern area, in the deepest part of the basin dated Oligo-Miocene to the present day.

Eocene Syn-rift petroleum system:

The Eocene petroleum system deals with the Eocene Tanjung non-marine section immediately overlying basement. Source rocks are dominated by coaly shales, organic-rich lacustrine shales (type I/II), and swampy coals (type III) of lake swamps with Ro around 0.6-0.7 % (Kaluku-1).

The basin modeling results indicate that the top of the Eocene syn-rift sequences entered the peak of oil generation at about 20 mya or Early Miocene and continuing to the present day, while the peak of gas generation at around 16 mya. The top of the oil and gas expulsions are generally at the depth of around 13,000 and 14,000 feet. One example of the recovered oil is the one collected in Kaluku-1 well (Figure 6). The oil is very waxy typical for lacustrine source rocks. The lacustrine source rocks were deposited in the grabens with some influence of terrestrial materials from the surrounding horsts (Satyana, 2015).

The reservoir rocks are sandstones of the fluvial, lacustrine, and deltaic systems. Although the reservoir could be stacks of thin sandstones, the porosity in this Eocene section is still high with an average of 30 % and permeability around 500 md in Kaluku-1 well. Conceptually, the high porosity should remain preserved if the reservoir is filled by early charge of hydrocarbon.

The intra-formational seals are discontinuous and allow hydrocarbon to possibly leak to the overlying reservoirs (Doust and Sumner, 2007). However, the thick Mio-Pliocene deepwater shales were distributed widespread across the basin in the east to become a regional seal. Seismic and geological interpretations indicate that simple faulted anticlinal, basement drape, and stratigraphic traps including fractured basement plays could exist in this play (Figures 13 and 14).

Oligo-Miocene Post-rift petroleum system:

In the Paternoster Platform, there could be some shallow marine carbonates present including reefal build-ups (Figure 14). Perhaps some carbonate slope conglomerates could also be well-developed on the northern flank of the platform, similar to the

Oligocene Berai Formation observed in the southern flank of the platform, ie. Ruby Field (Pireno et al., 2009). In this field, the gross carbonate thicknesses range 70-330 feet with net pay thicknesses of 10-280 feet and average porosity of 15-17%.

In the Ruby Field and surrounding areas, the hydrocarbon seems to be generated from a mixture of algal and terrestrial kerogens of the Eocene Tanjung Formation that have entering oil window in the Middle Miocene and gas window in the Pliocene. The present day oil window (Ro=0.7%) is estimated at about 16,500 feet and gas window (Ro=1.3%) approximately at 21,700 feet (Pireno and Darussalam, 2010). It is shallow lacustrine and fluvio-deltaic source rocks with an excellent source potential consisting of predominantly oil prone kerogen type II and gas prone kerogen type III. The isotopic data in the Ruby Field suggests that the gas has a modest biogenic methane component in addition to the thermogenic (Ariyono et al, 2013).

The Middle Miocene Sepinggan delta system has proven the presence of hydrocarbon accumulations in the Sepinggan region. Several oil and gas fields have already been discovered along with distribution of the delta lobe but are generally smaller size than those discovered in the Mahakam delta further to the north (Figure 11). The petroleum system in the Sepinggan region works very well, but the lateral and vertical extent seems to have constraint compared with those in the Mahakam delta system. The reservoirs are the late post-rift sandstones related to the Sepinggan regressive lowstand delta, and transgressive reefal carbonates. These main reservoirs are part of the Balikpapan Group dated as Miocene age (Susianto et al., 2012). The hydrocarbons discovered are mainly gas and condensate (Syarifuddin et al., 2008). It is generally sourced by type III source rocks deposited in a deltaic environment.

The top seal for the Berai carbonates is the shales of the Lower Warukin while the top seals for the Sepinggan Sandstone and Upper Warukin Formation are the intra-formational shales and the overlying shales. The hydrocarbon could migrate vertically and horizontally into the Sepinggan Sandstones and into the platform to fill the Upper Warukin carbonate reservoir or equivalent if it is sufficiently sealed.

Mio-Pliocene Deepwater petroleum system:

If the Sepinggan delta is able to provide sufficient source rocks and reservoir sandstones to the deepwater slope and fan lobe play towards the east, there will be another attractive petroleum system in the east within the Middle to Late Miocene deepwater sequences. The excellent analog for this exploration play system is the deepwater located immediately to the east of the Mahakam delta.

In the Mahakam deepwater system, the source rocks are associated with the reservoir sandstones and siltstones rather than the shales, and were transported together at the same time from Mahakam delta in the west into the deepwater basin in the east by turbidity currents (Guritno et al., 2003). The hydrocarbons discovered are gas and condensate related to type III source rocks. The organic fragments are scattered chaotically within the sandstones or organized into parallel laminae. Consequently, the "sweet-spot" should correspond with the high energy deposition of sand-prone reservoir intervals. The seals are provided by intra-formational and hemipelagic deepwater shales. Individual reservoir sandstone units are encased by intra-formational shales nearby (Guritno et al, 2003).

As the size of the Sepinggan delta is likely to be limited and smaller than the Mahakam delta, the source rock depositional model and volume which work well for the Mahakam deepwater region, might not be applicable for the deepwater region in the southern part of the North Makassar Basin. Consequently, the expected hydrocarbon presence in this region would be biogenic gas rather than thermally gas or oil.

The sediment provenance for the deepwater reservoirs in the northeast of the region is the Paternoster Platform rather than the Sepinggan delta due to its lateral extent and closer to the location of deposition (Figure 11). The carbonate debris materials could dominate the lithology.

Seismic interpretation indicates the presence of some strong discontinuous events over the Middle Miocene to Pliocene section. Some small deepwater channels and thin sheets are visible, but mostly difficult to recognize. These strong amplitudes could be related to the presence of biogenic gas. Further investigation is required to confirm.

CONCLUSIONS

Below are the summary and conclusions of the discussion presented in this paper. It is obvious that further observation and study is required to confirm and establish the concepts and interpretations:

(1) Current seismic interpretation and drilling results have strongly suggested that the basement

type beneath North Makassar Basin specifically in the southern portion is proven as continental crust.

(2) Major tectonics activity in the Tertiary occurred in Middle Miocene when the Paternoster Platform was uplifted and eroded, while rapid deepening of the basin occurred towards northeast. This resulted in the stratigraphic contact of the Eocene non-marine syn-rift section immediately overlain by the carbonate debris of deepwater deposits of Oligocene in age and younger.

(3) The Adang Fault with normal mode dipping and down-thrown to the north was initiated in the Early Oligocene. During the Middle Miocene the fault may have been reactivated to become a dextral strike-slip mode. This fault seems to extend further onshore towards the west to become an important feature on the border between the Kutai and Barito Basins.

(4) All of the sediments deposited on the Paternoster Platform are likely to be non-marine to shallow marine, while to the northeast are deepwater deposits, with the exception of the Eocene syn-rift section.

(5) The sediment provenance for the deepwater sequence mainly comes from the Paternoster Platform, with partial sources from the onshore Sepinggan area.

(6) Further interpretation indicates that the coarse structural grains in the region remain the same since the Eocene at the time of syn-rift initiation. No major structural grains have changed, with the exception of the Adang Fault movements intermittently varying over with time.

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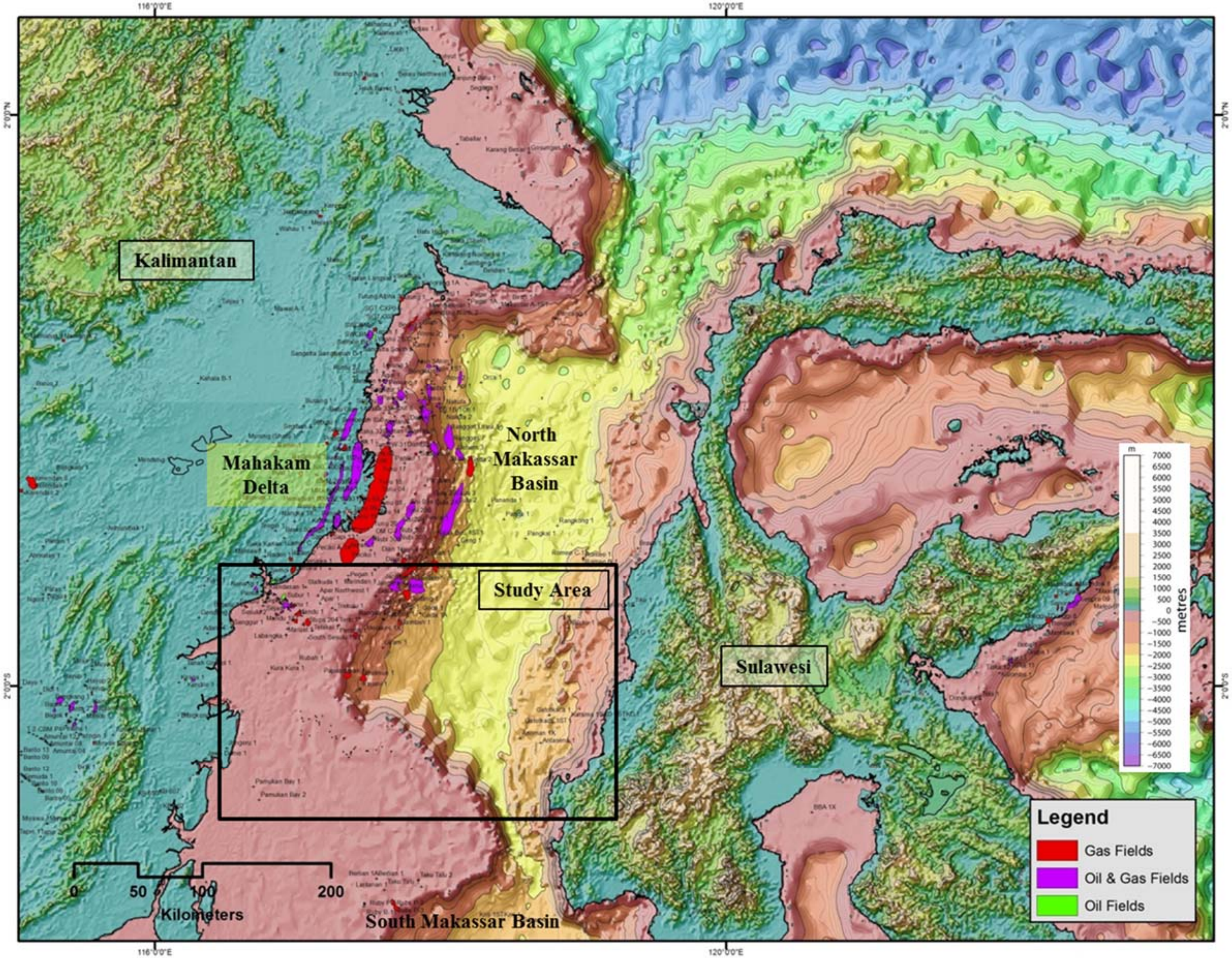


Figure 1 - Topographic and bathymetric map showing the North Makassar Basin overlain with the existing oil, condensate, and gas discoveries in the region (http://www.bandaarcgeophysics.co.uk/ei-topo.htm). The study area is located in the southeastern end of Sundaland Craton.

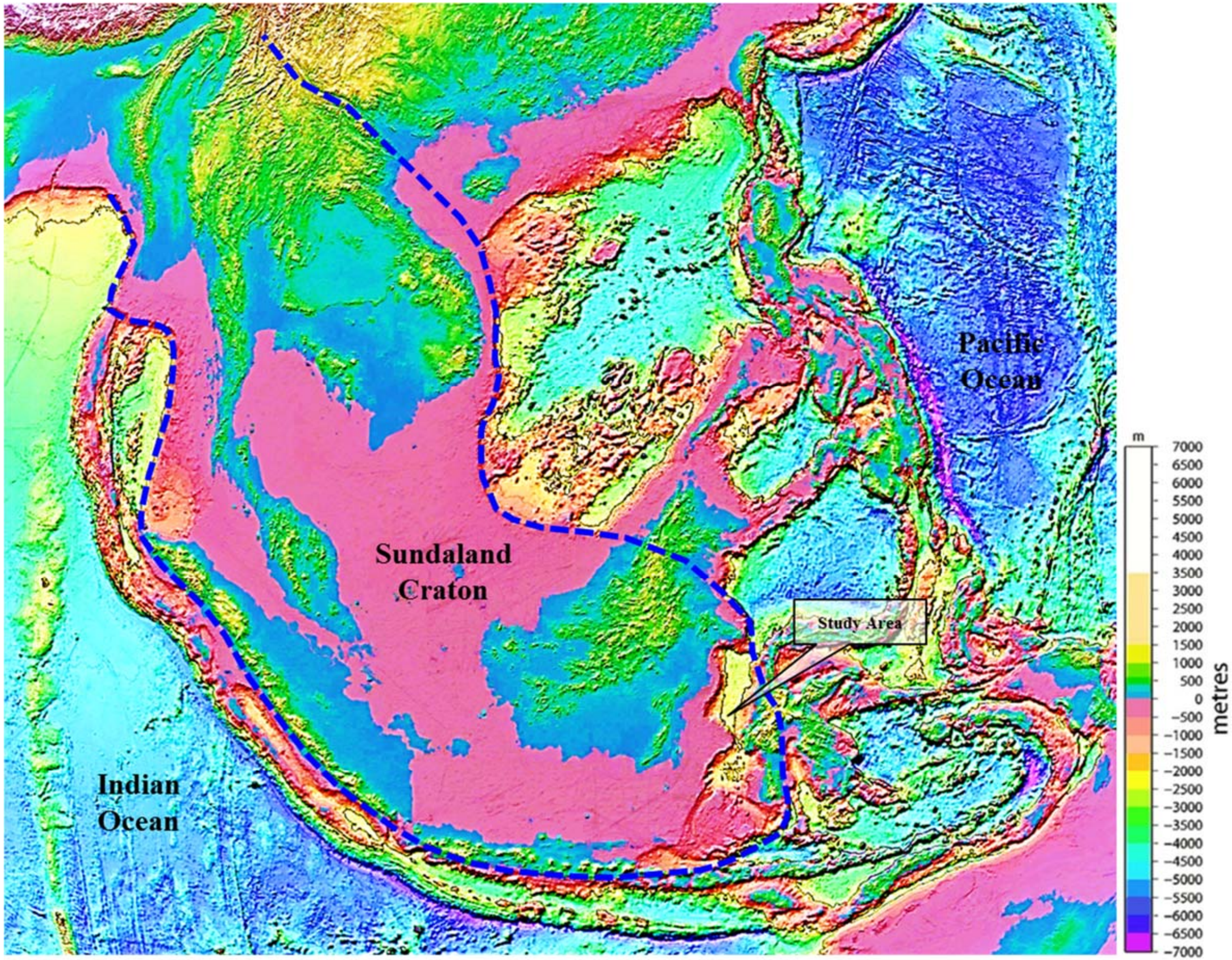


Figure 2 - Global map of the Shuttle Radar Topography Mission (SRTM) plotted in Google Earth showing the present day feature of Sundaland Craton outlined in dashed blue line (http://topex.ucsd.edu/kml/topo_srtm/topo_srtm.kml). The study area is located in the southeastern end of Sundaland Craton.

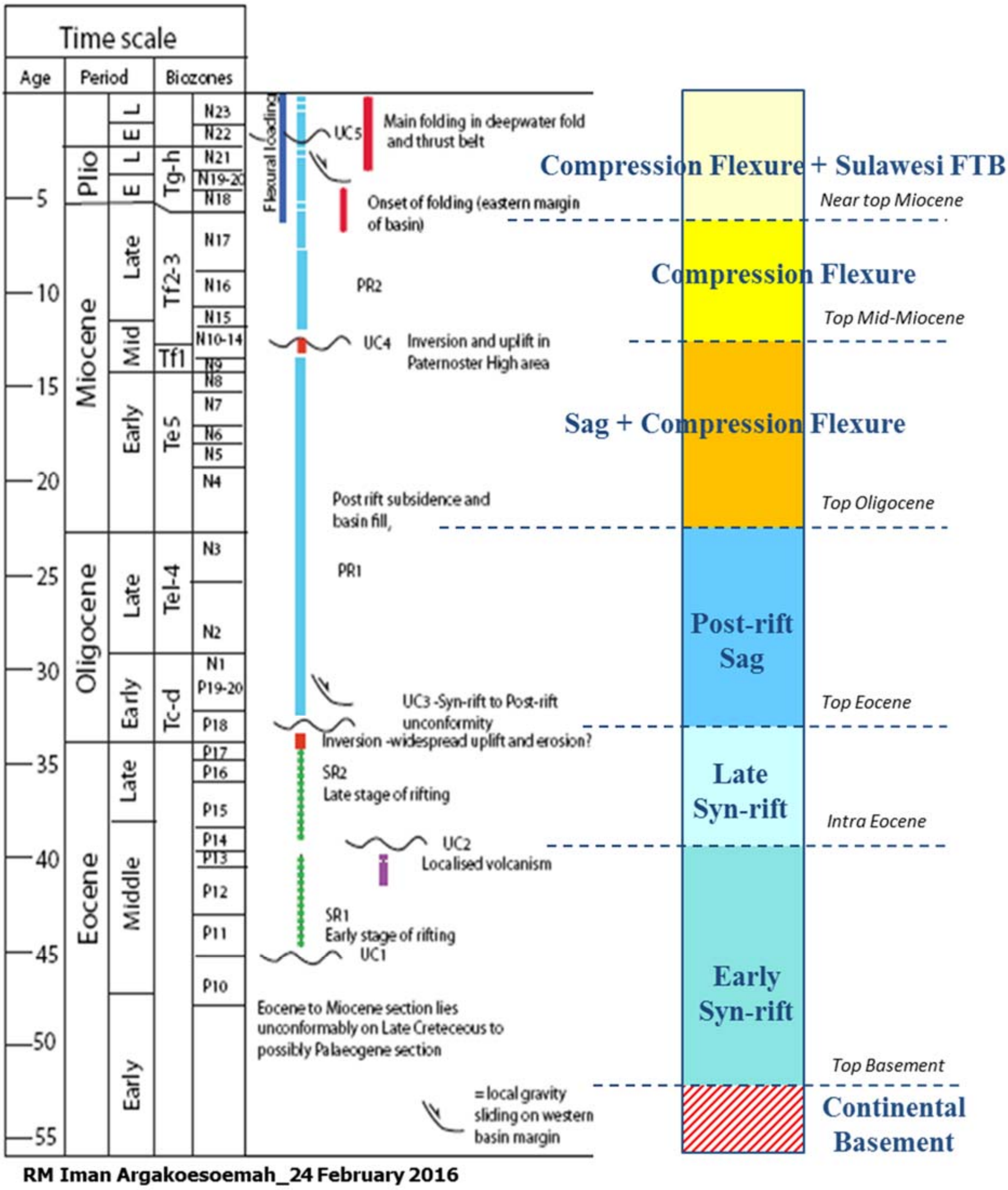


Figure 3A - Tectono-stratigraphic column of the southern part of the North Makassar Basin (see also Rousseau et al., 2015).

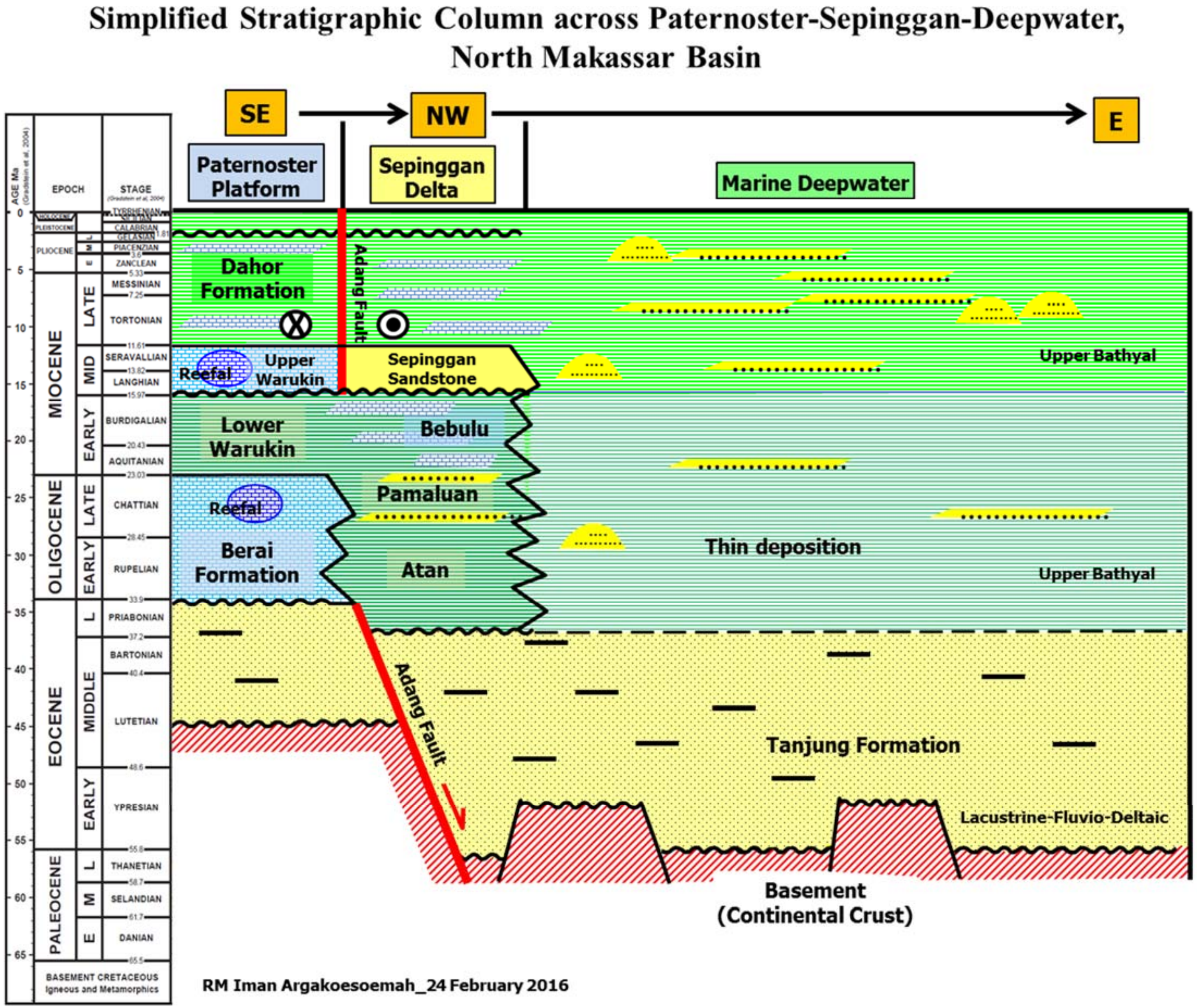


Figure 3B - A simplified stratigraphic column across the Paternoster-Sepinggan-Deepwater showing the stratigraphic units and their contacts including the Adang Fault activity.

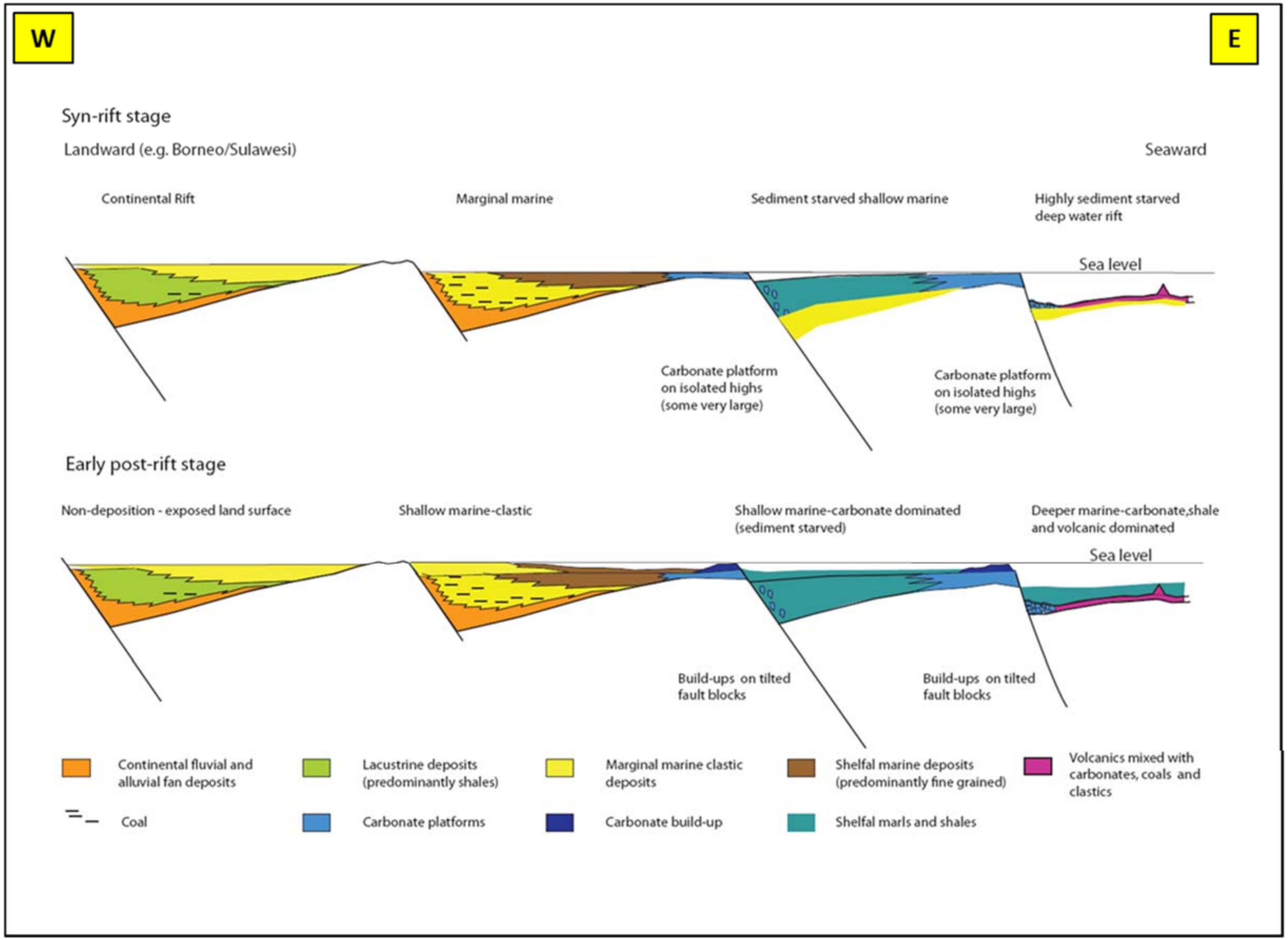


Figure 4 - A sketch illustrating the stratigraphic variation of syn-rift and early post-rift passing from Kalimantan in the west to the Makassar Strait in the east.

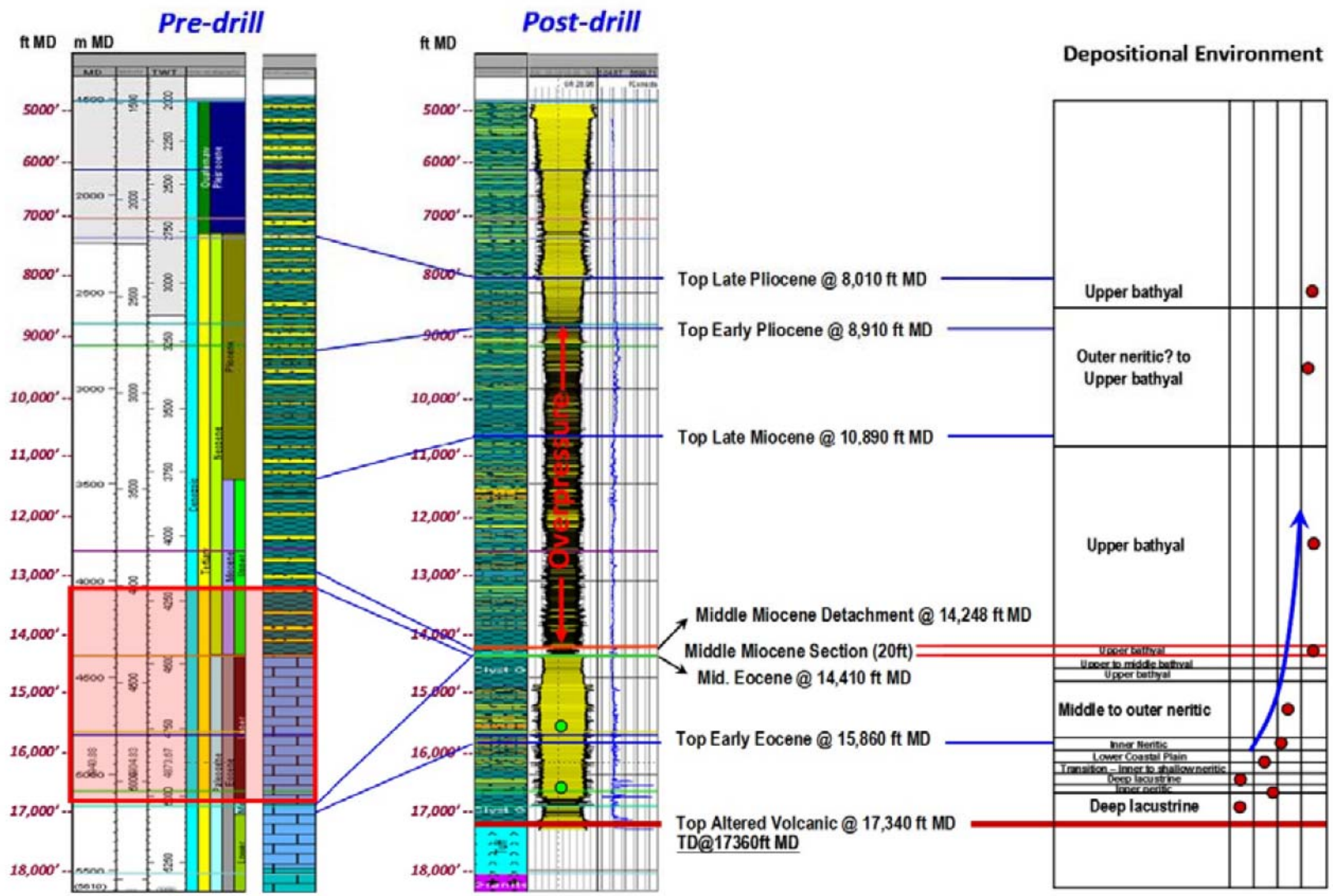
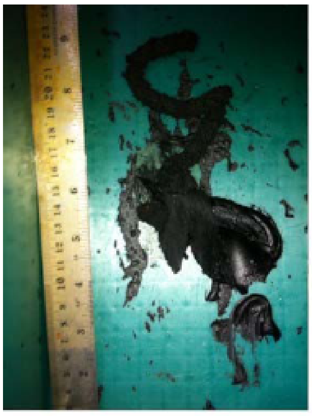


Figure 5 - Top sequences encountered in Kaluku-1 with their depositional environments (Satyana, 2015). The EOD is deepening towards the Plio-Pleistocene section.

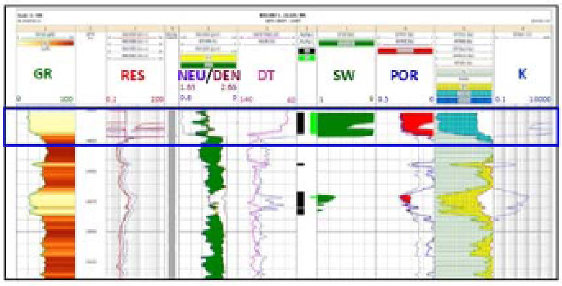


OIL 15,572'

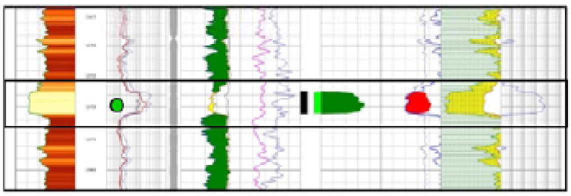
OIL 16,702'

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

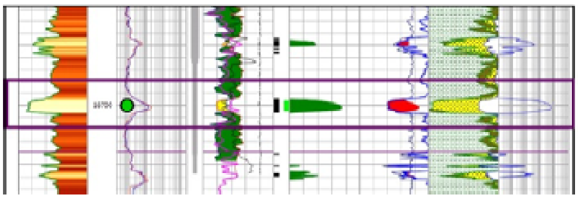
Kaluku-1 Postdrill



Mid Eocene Limestone (14893-14920')
- Mudstone to Wackestone, Packstone in part, Argillaceous
- Potential pay: 20 ft
- Porosity (average) 28%
- Permeabilities 100-200 mD
- Sw 50-60%



Middle Eocene Sandstone (15733-15753')
- Potential pay: 17 ft
- Porosity (average) 30%
- Permeabilities 450 mD
- Sw 30-40%



Early Eocene Sandstone (16694-16706')
- Potential pay: 9 ft
- Porosity (average) 30%
- Permeabilities 500 mD
- Sw 30%

Figure 6 - Geochemical analysis results of oil samples recovered from wireline chambers in Kaluku-1. The oil was collected in the Eocene reservoir sandstone stringers with an excellent porosity and permeability (Satyana, 2015).

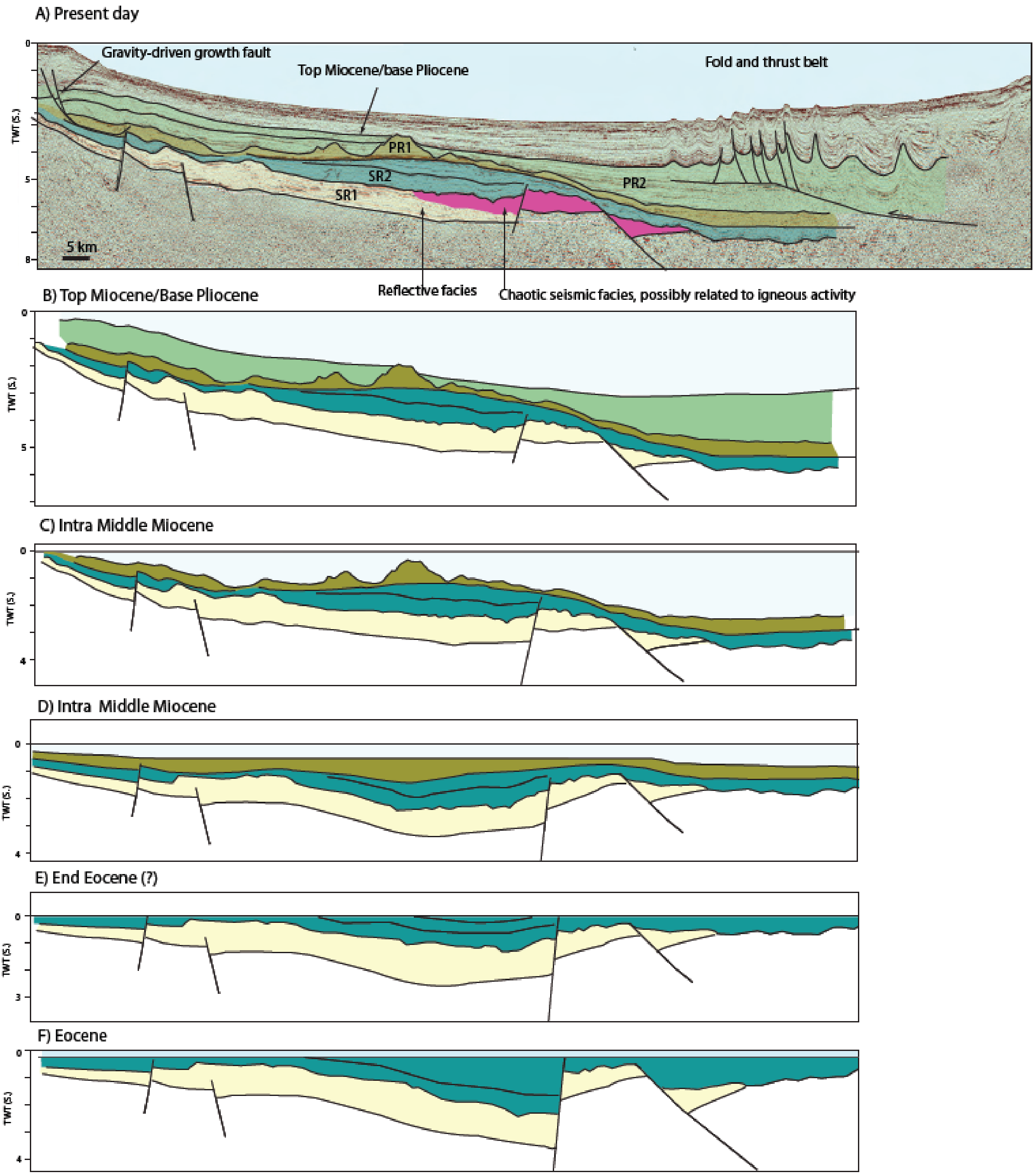
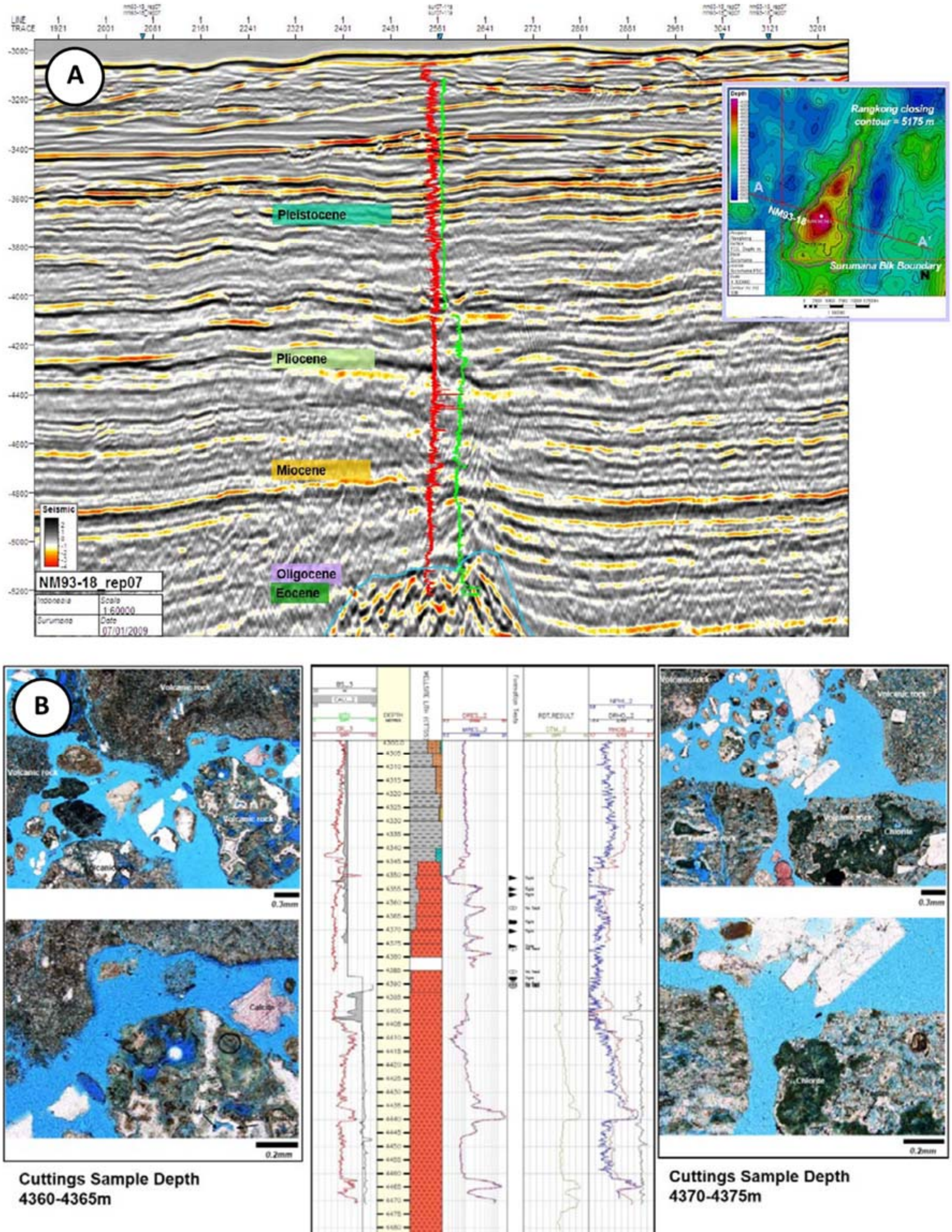


Figure 7 - SW-NE sequential restoration illustrating general large-scale structural events affecting the southern part of the North Makassar Basin. The preservation of mega-sequence stratigraphic units helps reconstruct the structural development of the region.



Figures 8A and 8B - (A) Rangkong-1 was drilled on a horst basement. (B) Cuttings and thin sections showing the lithology of basement which are volcanic basaltic igneous rocks with a porphyritic texture and abundance of glass (Satyana, 2015).

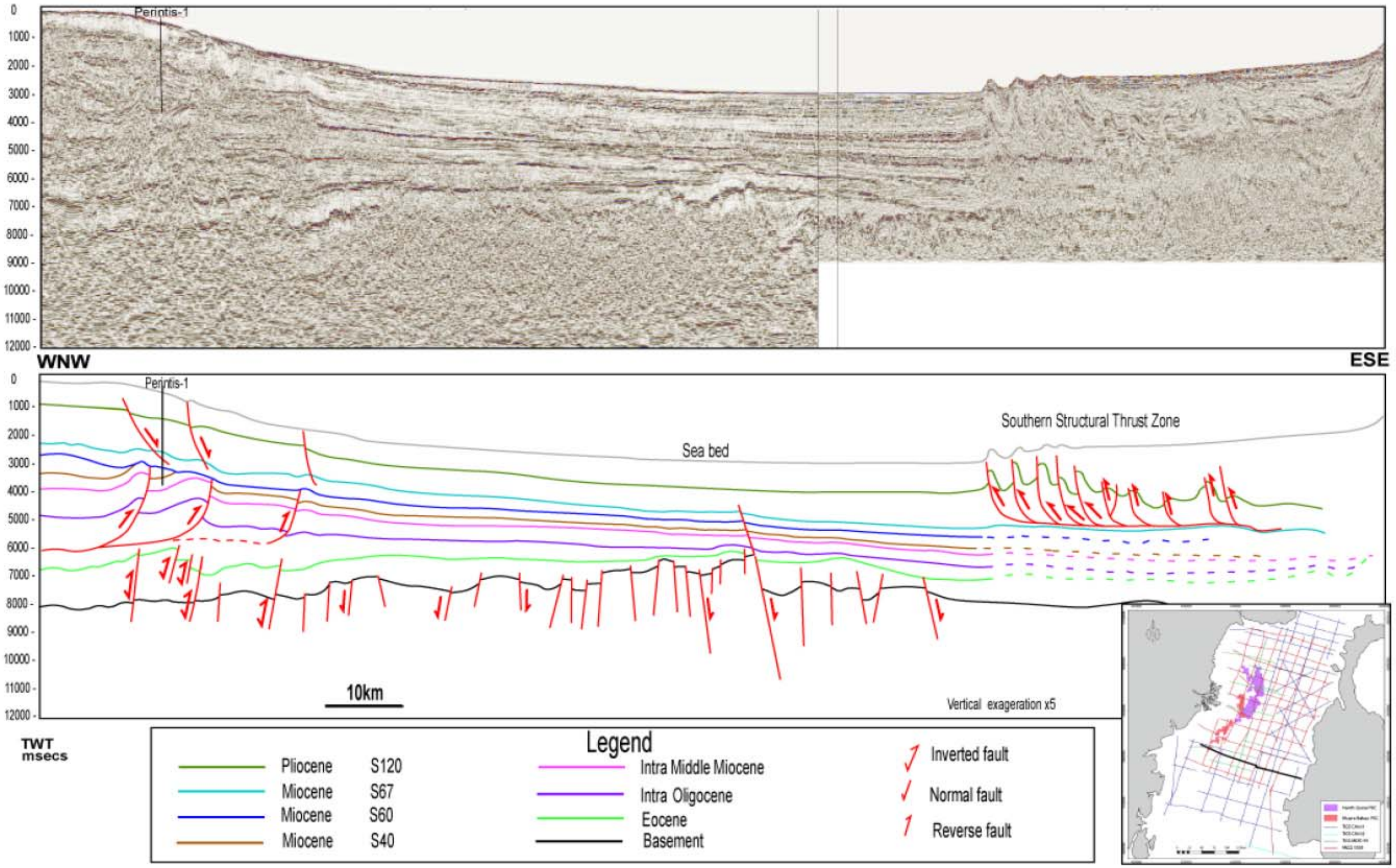


Figure 9 - WNW-ESE oriented uninterpreted and interpreted 2D seismic line showing the preservation of structural extension in the Eocene syn-rift section at the base and compressional thrust faults in the Plio-Pleistocene section at the uppermost part (de Negro et al., 2013).

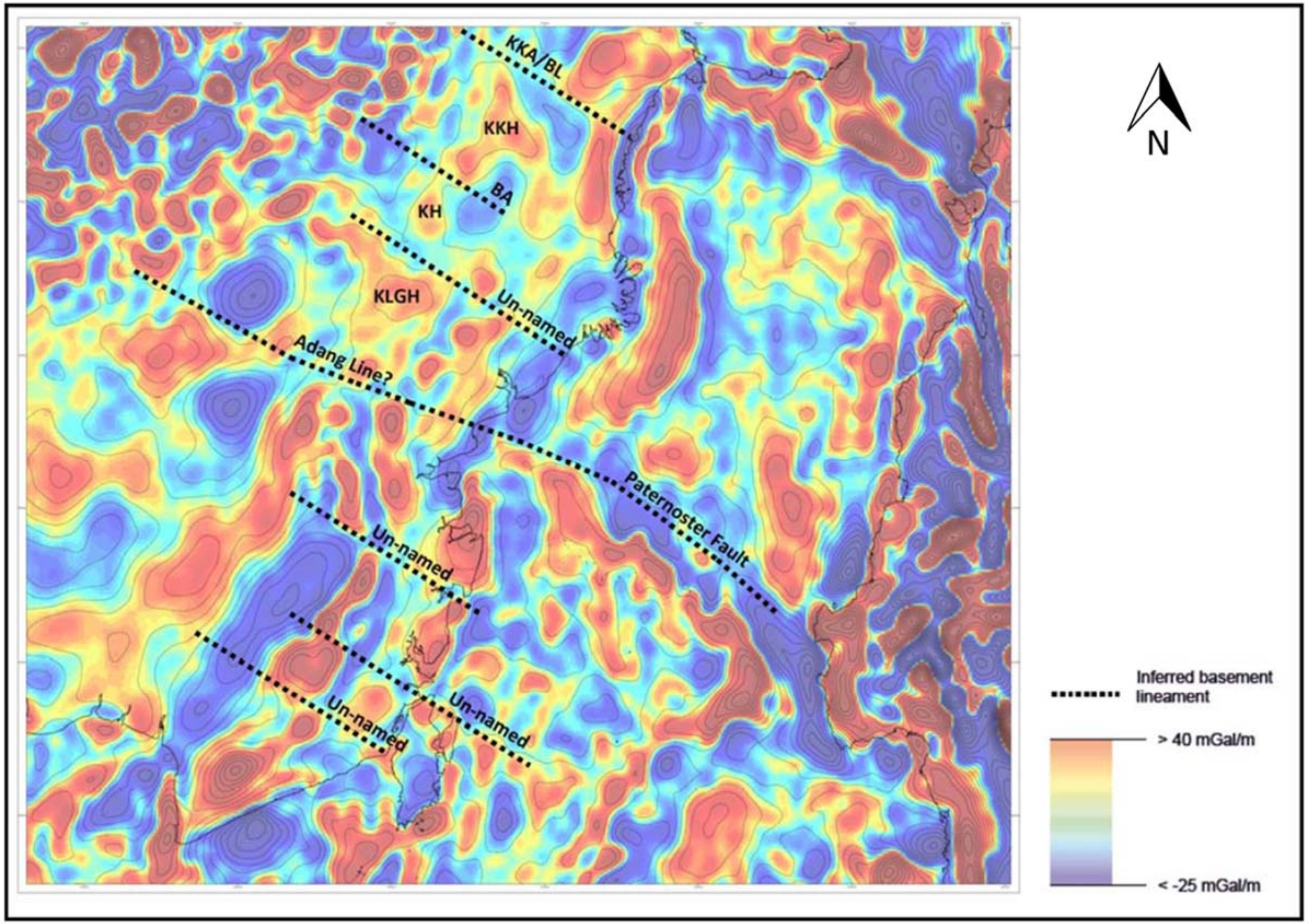


Figure 10 - Residual Bouguer anomaly – First derivative over East Kalimantan region (Witts et al., 2015). The Adang Fault seems to extend further towards west to become the border between the Kutai and Barito Basins. KKA/BL=Kedang Kepala Axis/Benegalon Lineament; KKH=Kedang Kepala High (gravity high); BA=Belayan Axis; KH=Kahala High (gravity high); KLGH=Kutai Lakes Gravity High.

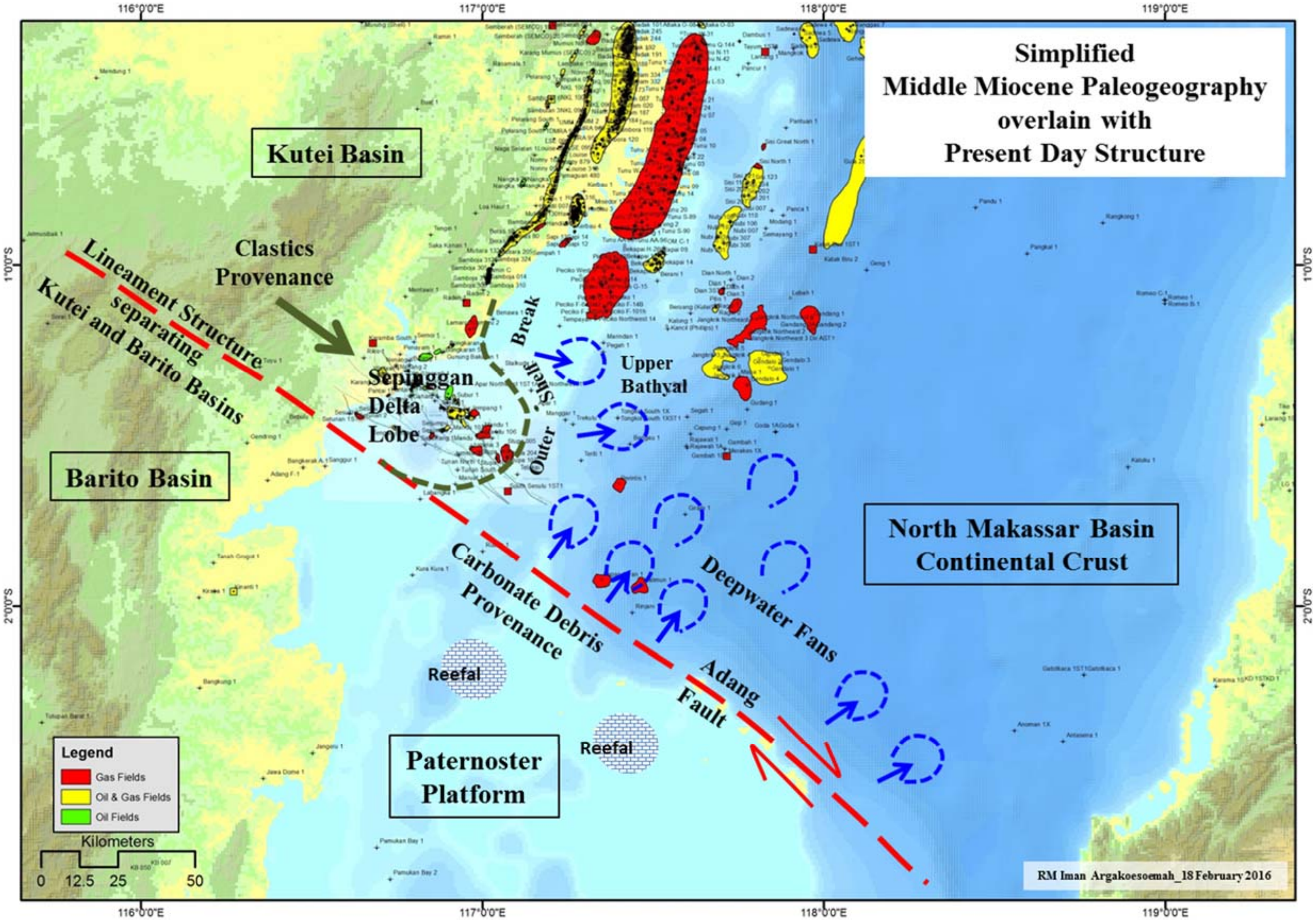


Figure 11 - Simplified paleogeography of Middle Miocene overlain with the present day structure showing major coarse structural elements and paleo-depositional styles.

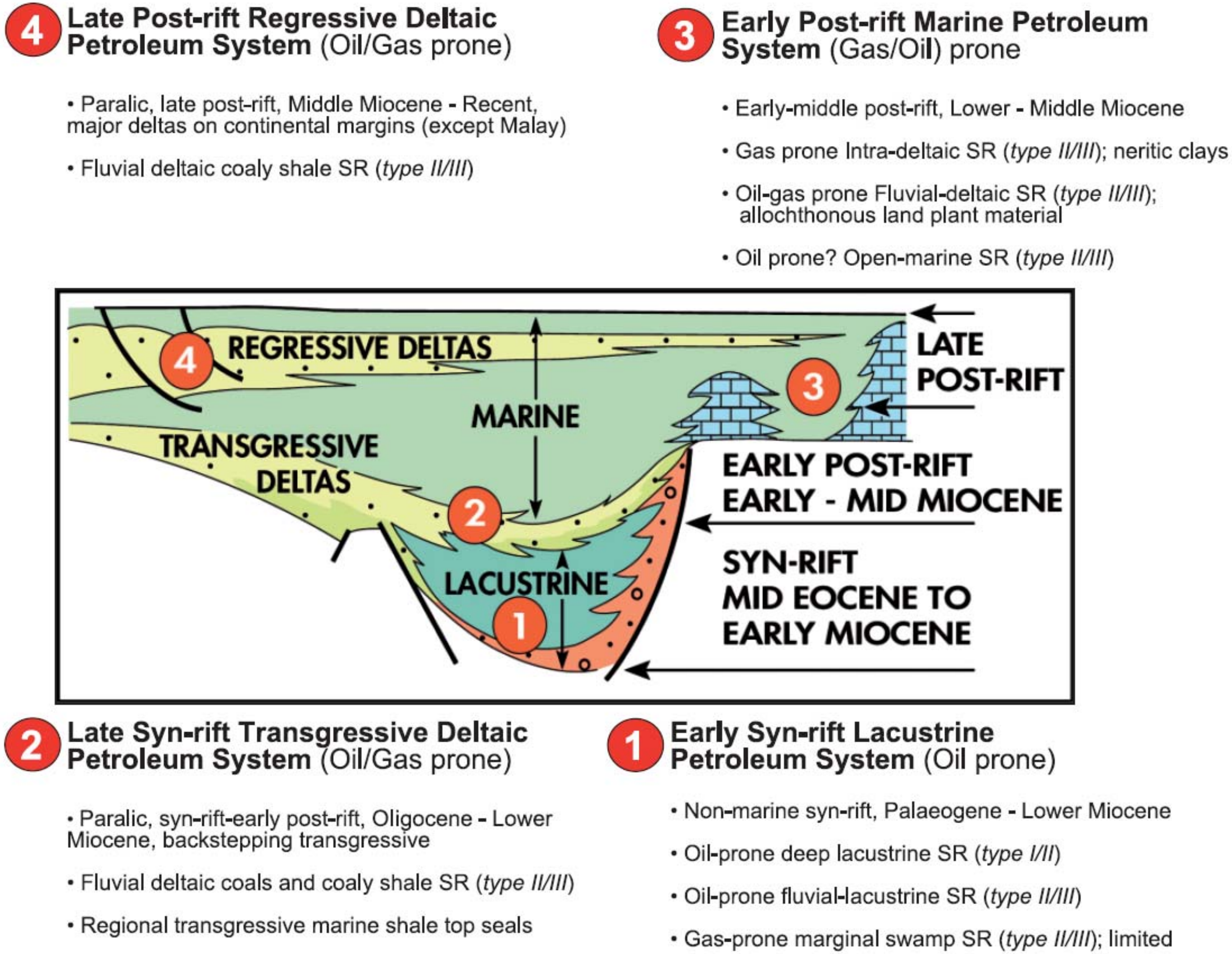


Figure 12 - Main petroleum system types (PSTs) recognized in Southeast Asia Tertiary basins (Doust and Sumner, 2007). Some of the PSTs are present in the southern part of the North Makassar Basin.

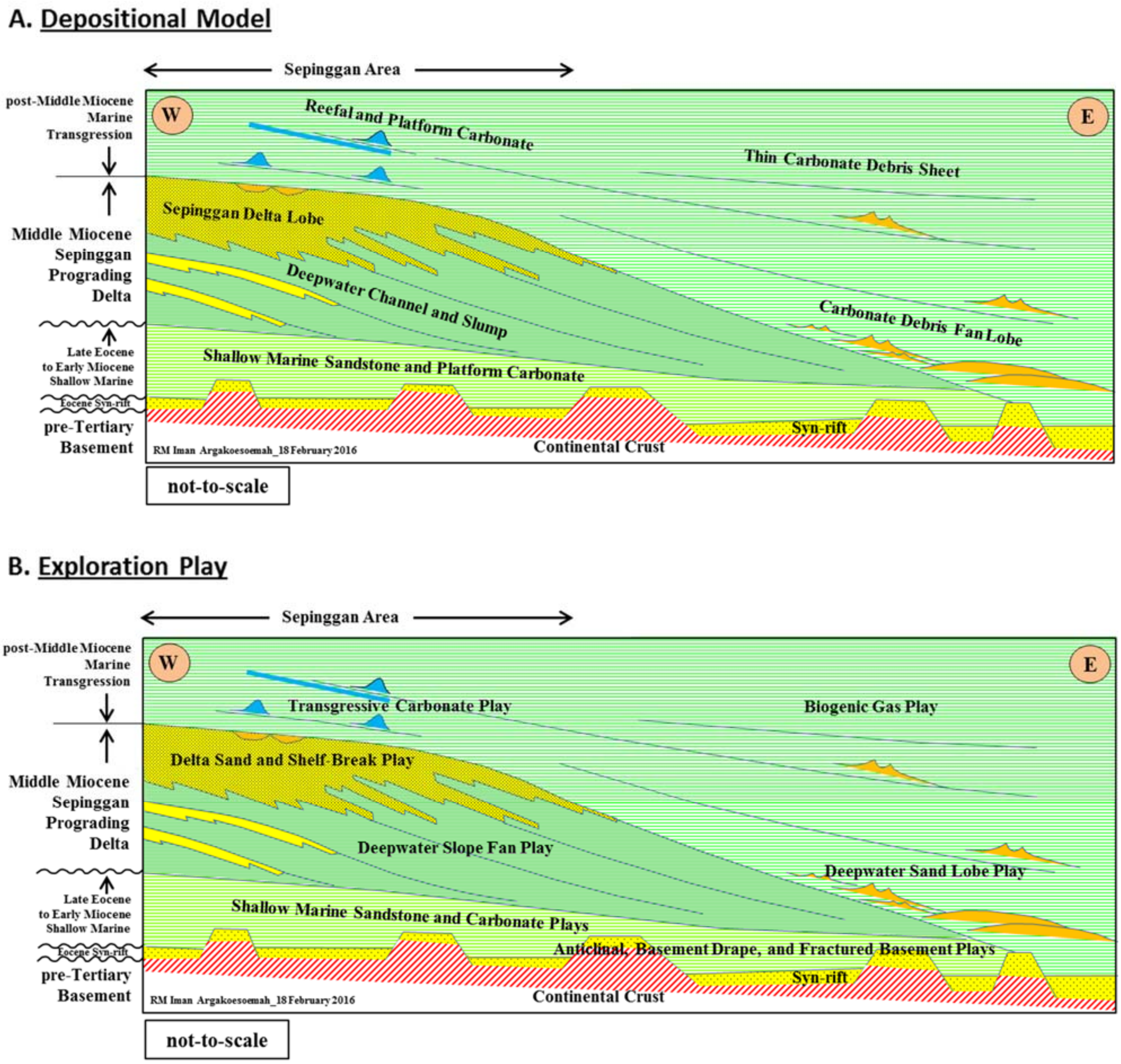


Figure 13 - Simplified cartoon of coastal-to-deepwater (a) depositional model and (b) exploration plays across the Sepinggan area in the southern part of the North Makassar Basin. At least ten exploration plays could be present in the region.

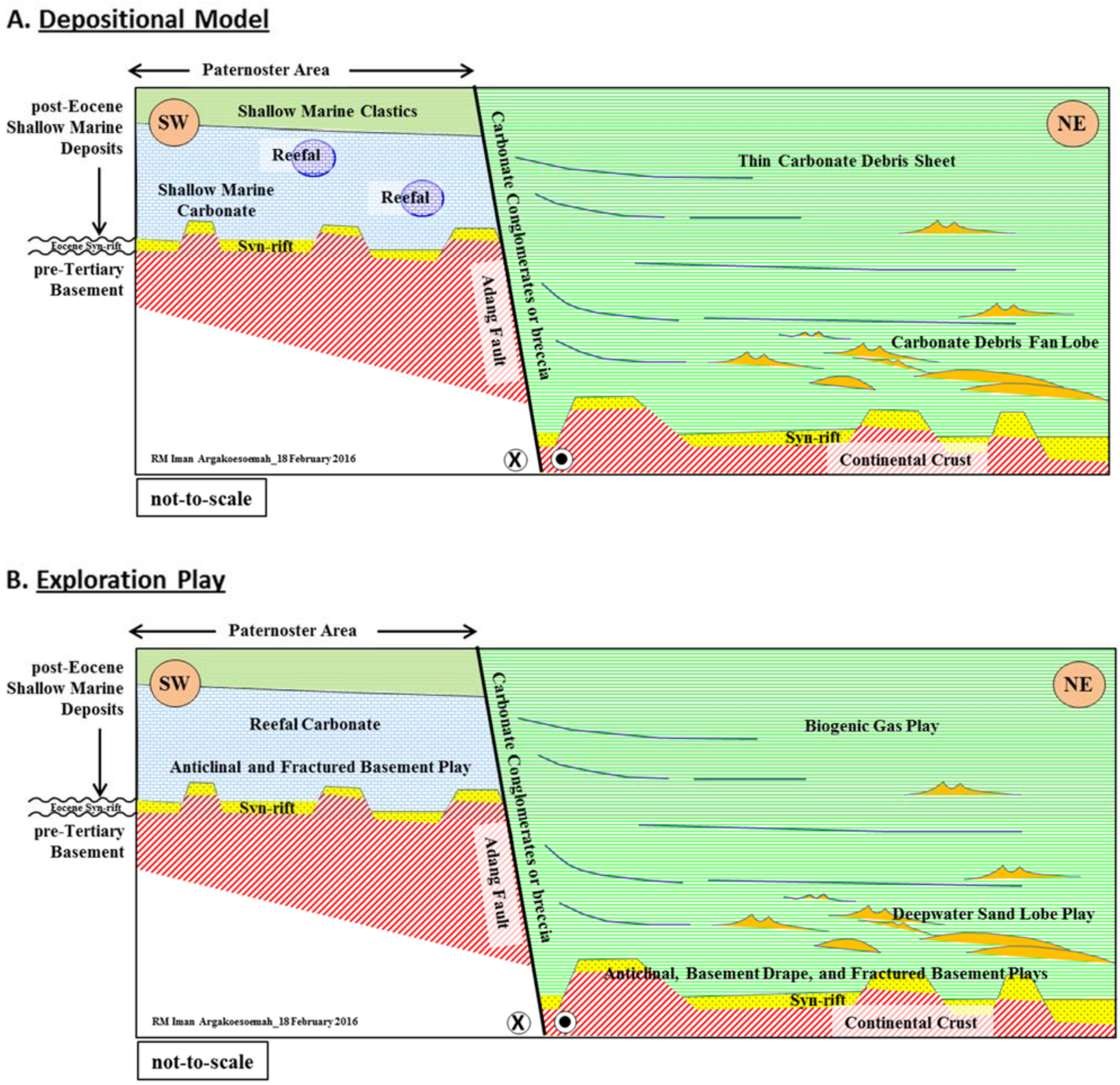


Figure 14 - Simplified cartoon of coastal-to-deepwater (a) depositional model and (b) exploration plays across the Paternoster area in the southern part of the North Makassar Basin. At least seven exploration plays could be present in the region.